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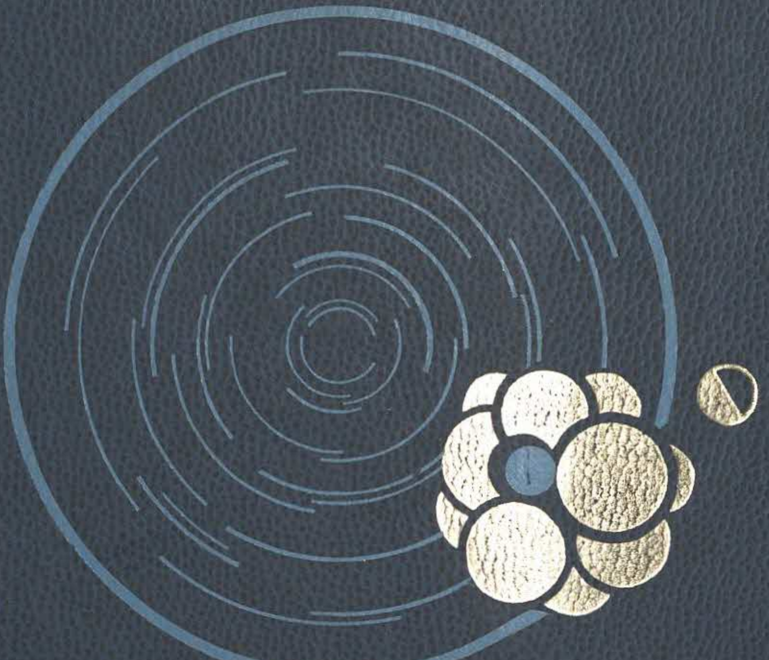
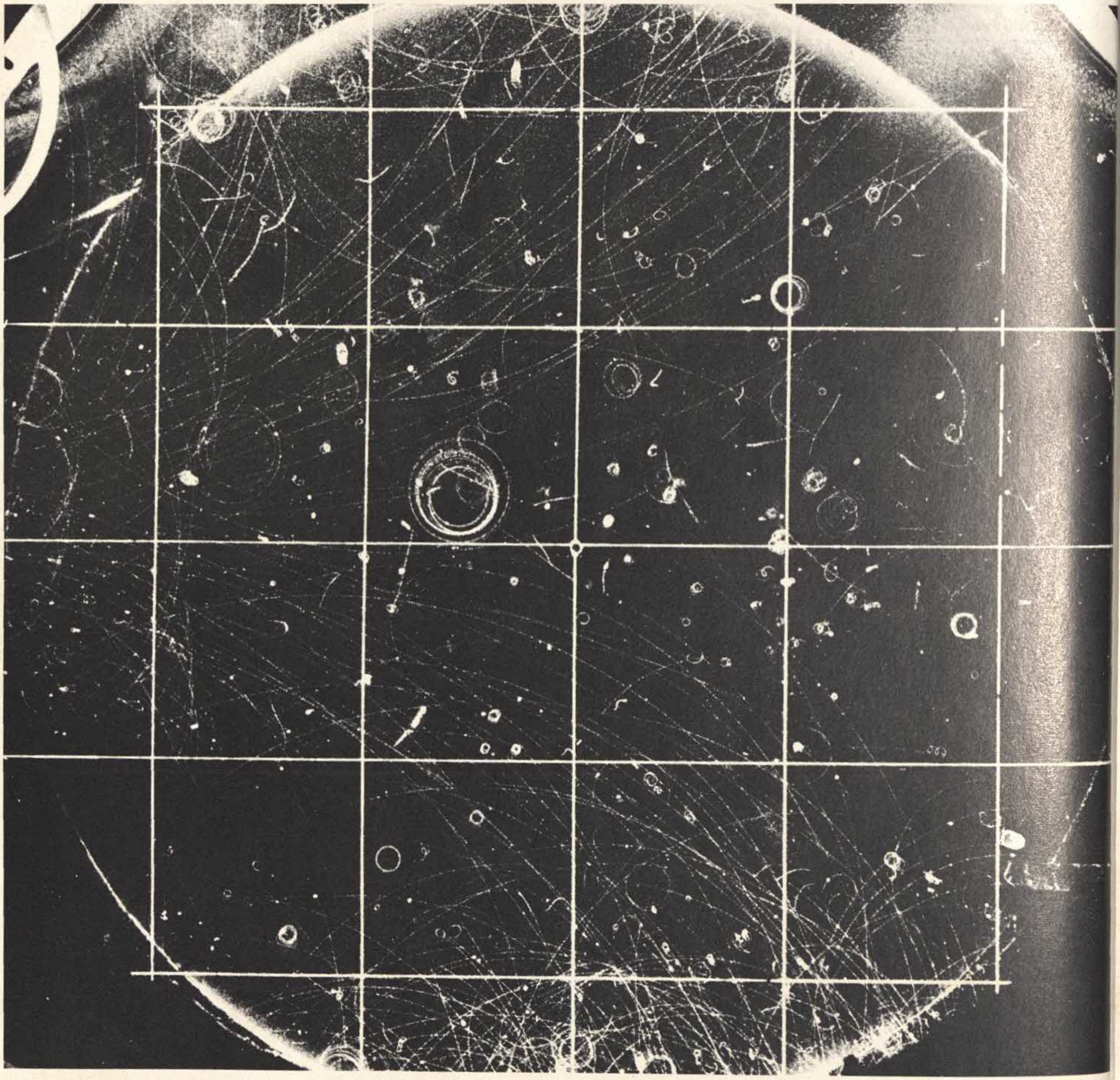
Illustrated World of Science Encyclopedia

Physics II:
ENERGY 1: HEAT,
ELECTRICITY
AND
MAGNETISM



THE WORLD OF SCIENCE



THE CLOUD CHAMBER — This apparatus makes visible the passage of high-speed ionizing particles.

THE WORLD OF SCIENCE

VOLUME

15

PHYSICS II

Energy 1: Heat, Electricity, and Magnetism

with

The Illustrated Science Dictionary

CREATIVE WORLD PUBLICATIONS, INC.
CHICAGO

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VOLUME 15

PHYSICS II

Energy 1: Heat, Electricity, and Magnetism

INTRODUCTION

Volume 15 deals primarily with the two important branches of physics—electromagnetism, and heat and thermodynamics.

Magnetic and electric phenomena have been known for centuries. Everyone knows that a compass needle always rotates to point towards the north pole, and most people marveled at the effects of static electricity while combing hair. Not until the nineteenth century, however, did an understanding of electricity and magnetism develop. Indeed, due mainly to the work of the Danish physicist Hans Christian Oersted, the French physicist André Marie Ampère, and the English physicist Michael Faraday, it was shown that these two areas, previously thought to be quite separate, were closely related—a changing electric current produces a magnetic field, and vice versa. The ultimate synthesis of all the then known experimental facts came in the 1870's when the Scottish physicist James Maxwell derived a concise mathematical basis for electromagnetism in the form of four vector equations. The fundamental principles of such diverse topics as the electric motor and generator, the transformer, electronic circuits, the transmission, propagation and reception of radio and television signals, radar and laser beams, are all embodied in Maxwell's famous equations.

One of the crucial features of Maxwell's theory was that electromagnetism is essentially a wave phenomenon, the theory being relevant in describing the character and properties of electromagnetic waves of all frequencies and wavelengths. These waves figure significantly in many different branches of physics. Visible light is crucial to human existence, but visible and ultraviolet light as well as x-rays belong basically to the area of atomic and molecular physics because these particular kinds of electromagnetic waves are associated with transitions between electronic orbits within atoms. The study of gamma rays provides valuable information about the structure of the core or nucleus of an atom. The long wavelength waves form the basis of the entire telecommunications systems—radio, radar, and television. These waves are also being used to great advantage in unraveling the mysteries of the sky, and have led, for example, to the recent discovery of pulsars.

Clearly, electromagnetic waves are of fundamental importance in nature. Maxwell's equations are analogous to Newton's definitive laws of motion and gravitation in mechanics; on them the whole of electromagnetism rests, making this subject one of the best understood in physics.

The present volume also examines some phenomena of heat and thermodynamics. The behavior of bodies when heated and cooled, and how heat is transferred, are of great practical importance in everyday life; indeed, it was the detailed investigation of these everyday events which led to the development of this particular branch of physics, culminating in the basic laws of thermodynamics discussed in articles of this volume.

An even greater insight into thermal phenomena can be derived through the knowledge of the more fundamental structure of matter, namely its description in terms of atoms and molecules. Thermodynamic quantities such as pressure and temperature can then be expressed as statistical averages of certain atomic properties, thus bringing about a further great unification of apparently diverse areas of physics.

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THE ELECTROMAGNETIC SPECTRUM

energy in the form of rays

The light with which the sun floods the Earth enables man to perceive the shapes of the things that surround him, and also their colors and their textures. The eye, a superb detecting device, is sensitive to those radiations from the sun known as visible light; other radiations, with characteristics analogous to those of light, are also emitted by the sun (and by other sources of energy) and are also apparent, directly or indirectly, to man. Described by scientists as electromagnetic radiations, these manifest a variation of characteristics that shade into one another over the entire range of their activity—a range known as the electromagnetic spectrum.

Even within that relatively small part of the spectrum occupied by the kind of radiation known as visible light, differences appear as variations of color. Light is generally thought of as white light, but a prism can break it into a band of rainbow colors. (A rainbow is caused by a water prism made up of mist, spray, or raindrops.) The light that results in each of these colors has specific properties: yellow, for example, is more conspicuous than violet; one color makes a strong impression on photographic emulsions while another does not; some colors encourage plants and bacteria to grow while others stunt growth.

Visible light is, by definition, that kind of radiation that is detected by the human eye (see Illustration 6). The other kinds of radiation have properties that are equally distinctive. Cosmic rays, reaching Earth from a distant star, the glow from a sunlamp, the heat from a fireplace, a radar signal or television image—all are manifestations of the same phenomenon, electromagnetic radiation.

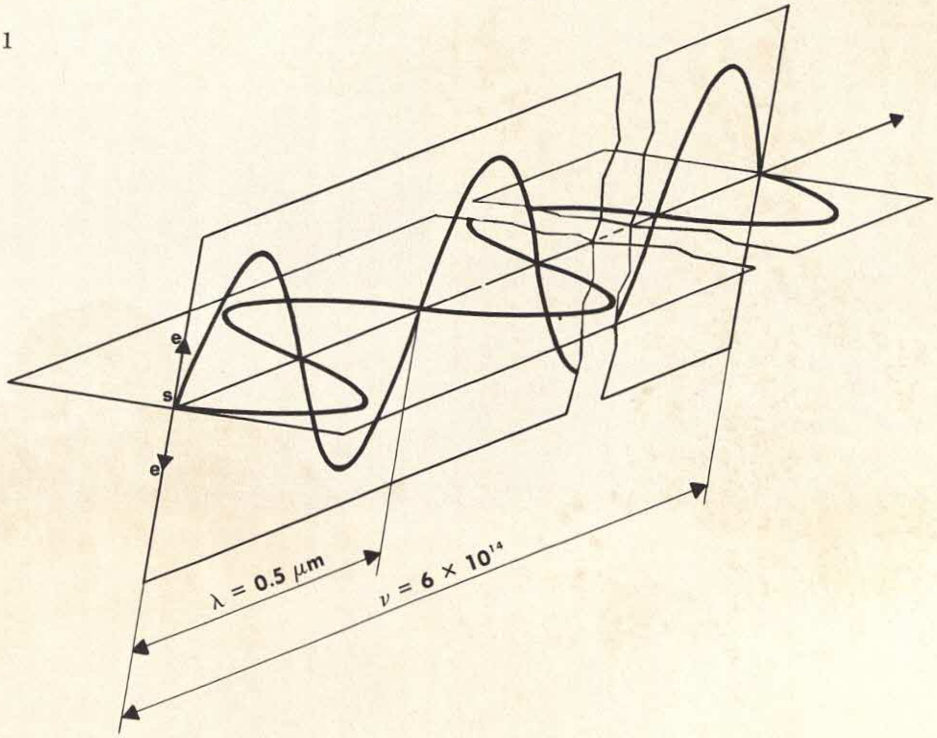
Most of these types of radiation are essentially a rapid variation of electric and magnetic fields resulting from the displacement of electrons of atoms from a larger, outer orbit to a smaller, inner orbit. This displacement is always accompanied by a release of energy of varying degree, which leaps outward at a constant, measurable velocity—about 300,000 km per second (186,000 mi per second)—a velocity most familiar as the speed of light.

The differences among the types of electromagnetic radiation can best be understood in terms of their wavelike character, which is roughly comparable to that of ocean waves that eventually strike a shore. The distance between the crests of the waves may be relatively more or less; if the former, the radiations are called long waves, if the latter, short waves. Similarly, the number of waves passing a given point or striking somewhere along the shore—given a constant rate of movement—would vary inversely; more short waves than long waves would pass that point in a given period of time. This can be stated in another way: shorter waves would pass that point with greater frequency. As a matter of fact, electromagnetic radiation is identified in terms of wavelength and frequency; the greater the wavelength might be, the lower the frequency.

Physicists are concerned with the forces that release energy of varying intensities (manifested in varying wavelengths and frequency). Of great concern are the properties of each type of radiation: whether a given type of radiation, such as some radio waves, has difficulty penetrating other objects; whether a radiation penetrates only "transparent" objects (as do visible light and radiant heat); or whether it penetrates many opaque objects (as do x-rays and gamma rays). Physicists are also concerned with the reactions of bodies struck by radiant energy: how they absorb, reflect, or otherwise react to the impact. Finally, physicists are concerned with the problem of producing electromagnetic radiation artificially, with practical connotations.

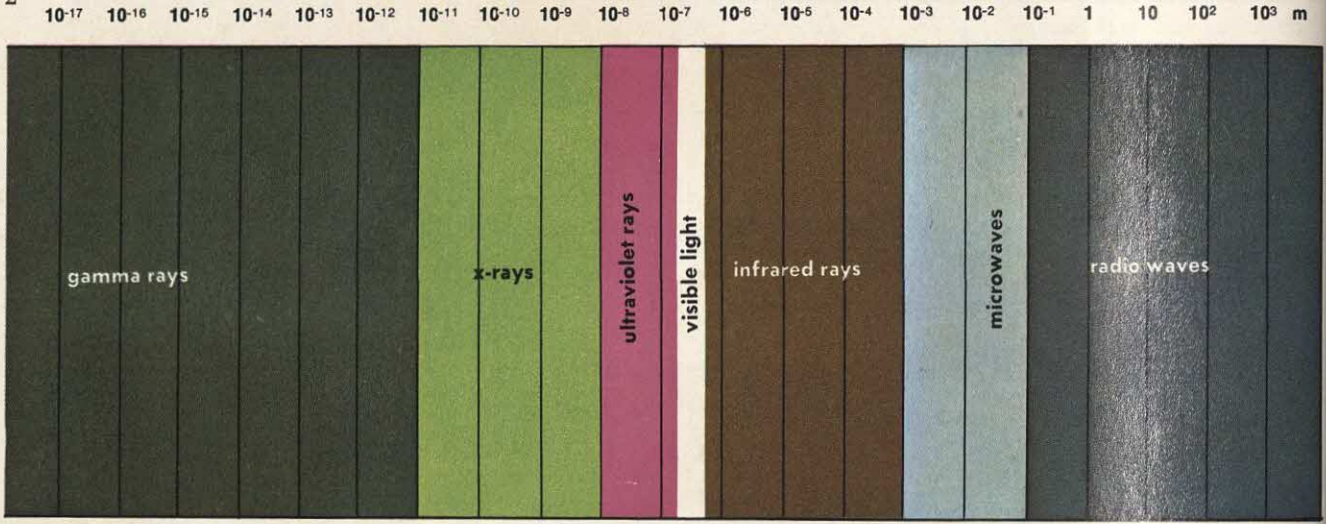
ELECTROMAGNETIC RADIATION—In this illustration the "ray" is represented by the straight line beginning at **s** on the left side; the arrow at the right side indicates the geometric direction in which the electromagnetic radiation is being propagated. If an electric charge were applied at a point along this line, the resulting electric field would oscillate in the directions of the two arrows **e**, because of an alternating force periodically exerted. It is rather as if a force were running along the ray, with its direction varying in time like the ordinate of the sinusoid **se**. At the point at which this electric force arrives, there is also an appreciable magnetic force that varies with the same periodicity, but that is exerted in a direction perpendicular to that of the electric force. These electric and magnetic "waves" proceed along the ray at the velocity of 299,793 km/sec (186,282 mi/sec)—the speed of light. In one instant, therefore, quite a large number of sinusoidal crests that represent the electromagnetic radiation passes each point along the ray; the number of crests (that is, of waves) that pass is called the frequency of the electromagnetic emission. In the case of light, this frequency is very great—6×10^{14} per second. The distance between the two crests is called the wavelength, and is very small (in this illustration, $0.5\ \mu m$). In scientific usage, frequency is usually denoted by the Greek letter ν (nu), the wavelength by the Greek letter λ (lambda) and the velocity of light by the letter c. The resultant formula is $\nu = \frac{c}{\lambda}$.

1



THE ELECTROMAGNETIC SPECTRUM—In order to illustrate all the various types of radiation in one diagram, it is usual to construct a scale on which are marked the wavelengths of the different radiations. On this scale are marked instead the approximate ranges of each type of radiation according to their wavelengths in meters, as if there were no overlapping or merging. These divisions are arbitrary; the name of the type of radiation shown in a particular range of wavelengths (and this would apply to frequencies as well) depends on the way in which the radiations are generated, or on their properties; some radiations have properties in common, or change very gradually from one to another. The divisions shown in this diagram are, therefore, not precise, but they are useful for indicating the general band of wavelengths occupied by each type of radiation.

2



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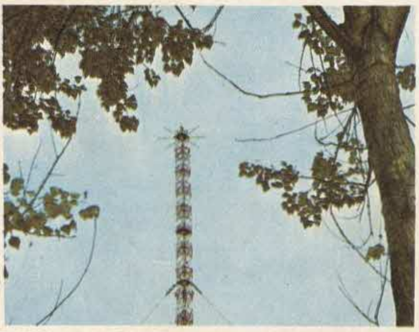
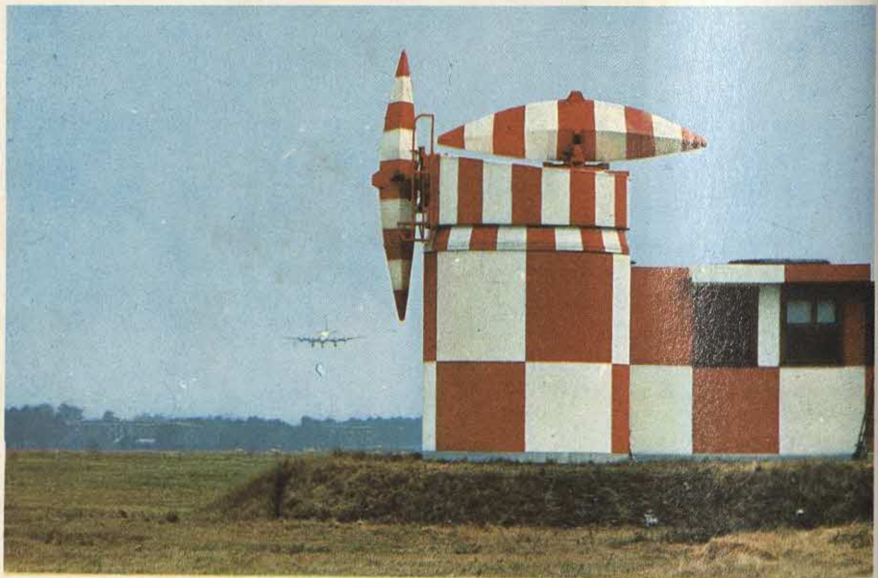


RADIO WAVES—These are the electromagnetic radiations with wavelengths ranging from about 10^{-1} m (10 cm) to more than 10^{5} m (100 km). They are produced naturally by the oscillations of charged particles in the atmospheres of many stars and in the interiors of some nebulas. They are produced artificially for the transmission of telegraphic signals, the human voice or other sounds, and television images. Transmitters that cause electrons to oscillate within a metallic conductor, or antenna (illustrated), produce these radio waves for practical purposes. Radio waves are identified not only according to their wavelength bands, but according to their frequencies, in terms of cycles per second, more commonly called hertz (Hz), after the German physicist Heinrich Hertz, who proved the existence of electromagnetic waves. Frequencies corresponding to the wavelengths of radio waves include the span from less than 3×10^{4} Hz (for the longest) to 3×10^{9} Hz (for the shortest).

4



MICROWAVES—These are the electromagnetic radiations with wavelengths ranging from 1 mm to 10 cm (10^{-3} to 10^{-1} m), and with frequencies correspondingly from 3×10^{9} to 3×10^{11} Hz. Experiments prove that, like light, microwaves are propagated in straight lines—that is, along lines of sight—and are reflected and refracted when they cross substances such as pitch. Microwaves are naturally emitted by many celestial bodies and are artificially produced by radar equipment (illustrated), which detects distant objects and determines their distances.

5

INFRARED RAYS—These are electromagnetic radiations with wavelengths ranging from about .0007 mm to 1 mm (10^{-7} to 10^{-3} m). They are called infrared rays because the English astronomer Sir William Herschel, when analyzing the properties of light, discovered that each portion of the visible spectrum produced by ordinary sunlight heated a thermometer to a certain intensity—and that the intensity increased when the thermometer was exposed to radiation below the range of the spectrum occupied by red light (the visible light with the longest wavelength). Infrared radiation is produced naturally at all temperatures by warm bodies, and can be produced artificially by extremely high-frequency radio transmitters. The stars, including the sun, are powerful sources of infrared rays, which are also produced by such diverse objects as a hot iron, and even the human body, although each emits rays of different wavelengths. These rays are scarcely detectable by man; the human retina can barely perceive wavelengths as low as 8.5×10^{-7} m, but the skin may be highly sensitive to infrared radiation. Practical uses of infrared radiation range from photography to the electric oven to the air-to-air guided missiles with "heat-seeking" homing devices. A commercial infrared lamp is illustrated.

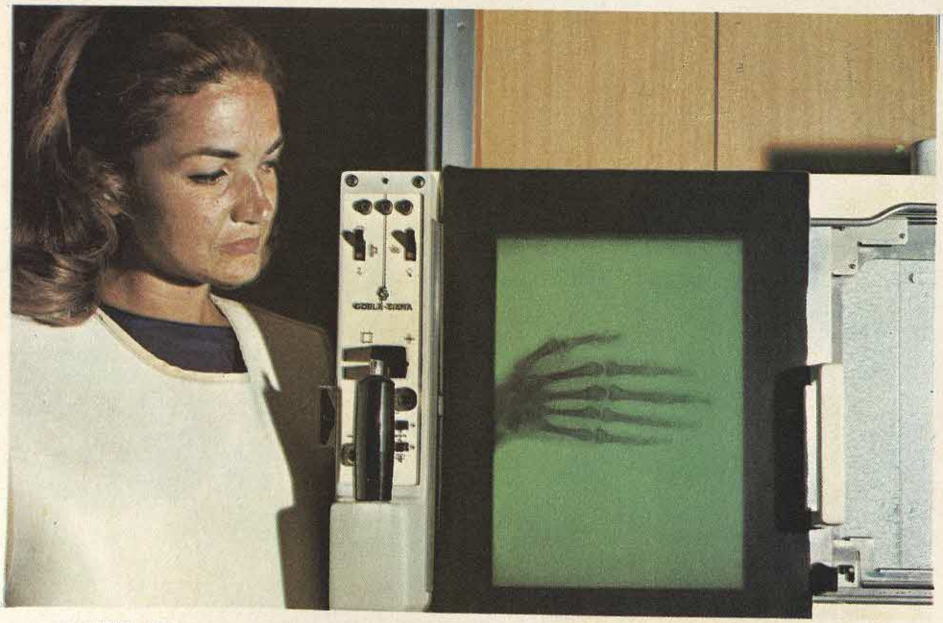
VISIBLE LIGHT—These are electromagnetic radiations with wavelengths ranging from about 0.0004 mm to .0007 mm. (Inasmuch as .0001 μm, or 10^{-10} m, is equivalent to 1 Ångstrom, it is more convenient to measure the wavelengths of visible light in Ångstroms [Å]: 4,000 to 7,000 Å.) Variations in wavelength, within this band, appear to human eyes as variations in color, from violet at the 4,000-Å end to red at the 7,000-Å end of the band. Visible light is produced in various ways: by an electron leaping from an outer orbit to a slightly smaller one or by the collision of an electron with another electron or another atom.

6

7

ULTRAVIOLET RAYS—These are electromagnetic radiations with wavelengths ranging from about 100 Å to 4,000 Å. Ultraviolet rays have many properties analogous to those of visible light. They also have a powerful chemical action; they are capable of detaching an electron from an atom, that is, they can ionize the atom. After being ionized, many atoms or molecules undergo chemical reactions. Some substances struck by ultraviolet radiation emit it again in the form of visible light; this phenomenon is known as fluorescence. For example, the mineral illustrated was photographed under ultraviolet radiation, which caused certain parts of the mineral to fluoresce—to emit visible radiation. Ultraviolet radiation can result from all the various leaps of electrons from the outermost orbits of atoms; this also occurs in black bodies at very high temperatures, and in plasma. The stars, including the sun, are very intense sources of ultraviolet radiation.

8



X-RAYS—These are electromagnetic radiations with wavelengths ranging from about 0.1 Å to about 100 Å. They are produced by electrons that leap from the outermost orbit of an atom to its innermost orbit, very close to the nucleus. They are also produced as a result of the rapid braking action that follows a collision between an electron, traveling at a velocity approaching that of light, and other atoms. Such collisions occur naturally in the interior of stars. They can be produced artificially in x-ray tubes, which are used widely in diagnostic medicine and for experiments in physics.

GAMMA RAYS—These are electromagnetic radiations with wavelengths less than 0.1 Å. They have the same properties as x-rays: they penetrate matter readily, and they detach electrons from atoms, even those that are very close to the nucleus and hence most subject to the electrical attraction of the nucleus. Gamma rays are produced when the nuclei of atoms are agitated by the emission of nuclear particles in the process of radioactive disintegration. Some nuclei emit gamma rays with wavelengths exceeding 0.1 Å (the usual "border" between gamma rays and x-rays). Many of the gamma rays present in cosmic radiation, although of very small wavelength, are produced by particles undergoing braking processes quite similar to those that produce x-rays.

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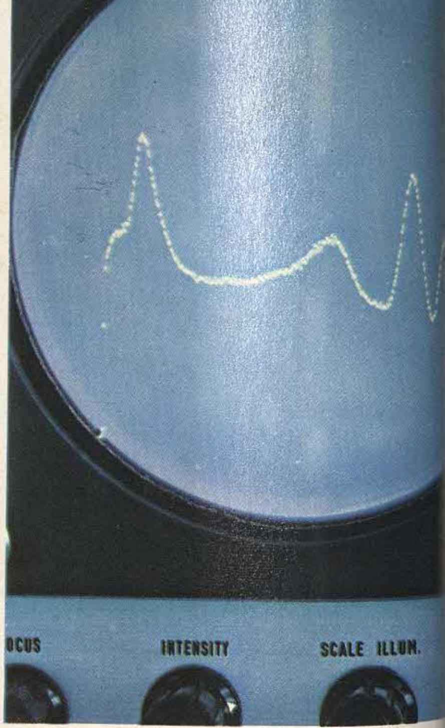


THE PRINCIPLE OF HUYGENS

a wave theory of light

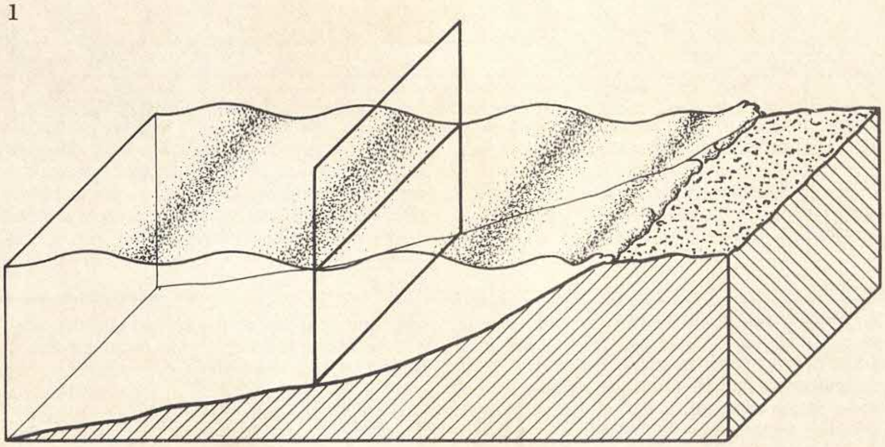
Optics is that branch of the science of physics concerned with light: its origin, its behavior, its effect on matter. Light is known to originate through the alternations of an electric field and a magnetic field, and can be defined, therefore, as a type of electromagnetic radiation with the wavelike characteristics of all such radiation. On the other hand, many optical phenomena can be studied by ignoring these wavelike properties and considering light as a ray that is propagated in a straight line, that penetrates some kinds of matter but is incapable of penetrating other kinds, and that undergoes reactions explicable in geometrical terms. The latter division of optics is geometrical optics, as distinguished from physical optics, which takes into account the wavelike properties of light rays.

It is, therefore, appropriate to begin a study of physical optics by defining the Huygens principle, and by stating a basic theory for the understanding of transverse waves regardless of their composition. Inasmuch as the waves in a body of water are comparatively familiar, easily reproduced in a laboratory, and easily understood, they may serve as models for all other kinds of waves.

THE WAVE FRONT—If a pool of still water is disturbed at a given point on its surface, say, by a pebble being thrown into it, concentric rings will appear around the disturbed point and spread in widening circles until interrupted. When examined closely, these waves are seen to be composed of alternating crests (high points) and troughs (low points). If the spreading could be "stopped" at some point, as by taking a photograph, an outermost ring would appear. All the particles of water along that ring would have moved the same distance from the point of disturbance, and would also be at the same distance in relation to the surface of the water, whether along the crest, along the base of the trough, or at some intermediate point.

The illustration shows a small section of water, from surface to ocean bed, approaching a shoreline. Four complete waves appear, beginning with a trough at the left end. (A transparent rectangle is shown at a right angle to the direction of the wave and following the trough at the end of the second wave.) A straight line along the crest, along the trough (such as the line in the center of the rectangle), or anywhere parallel to these, is the locus of all the particles of water that have simultaneously reached a certain level and distance from the disturbance. All particles in this situation are said to be "in phase," and the locus of all particles in phase at any one time is designated a wave front.

1



ELECTROMAGNETIC WAVE FRONTS—The electromagnetic vibration that radiates from an atom and may assume the aspect of light is propagated uniformly in all directions until it encounters something it cannot penetrate. The light wave has the same sinusoidal form, with alternating crests and troughs, as a wave that ripples along the surface of water. If the source of propagation is assumed to be the center of a sphere, as in this sketch, and if the wave is propagated at the same speed in all directions, all points at a given distance from the source will be either along the crests of the wave **aaa,** or along the troughs **bbb,** or somewhere in between. In this case, the wave fronts will not be a ring or a straight line (along a section of that ring) but a sphere. This applies to all electromagnetic waves—whether these are gamma rays, x-rays, ultraviolet rays, infrared rays, or visible light.

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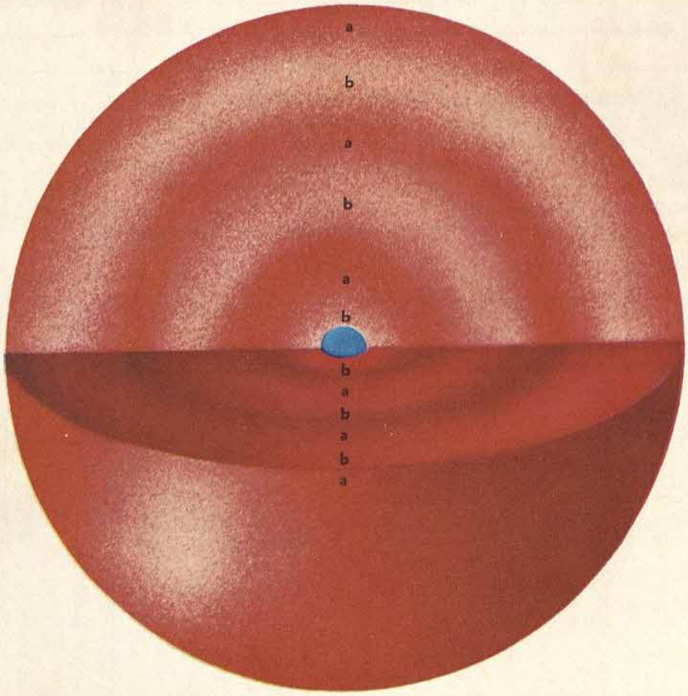

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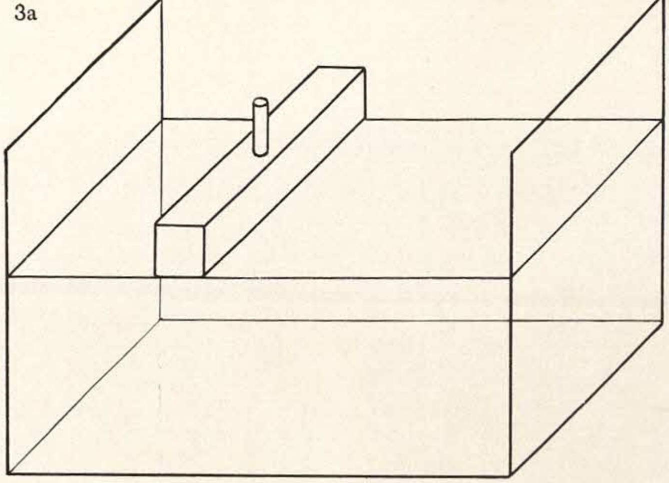

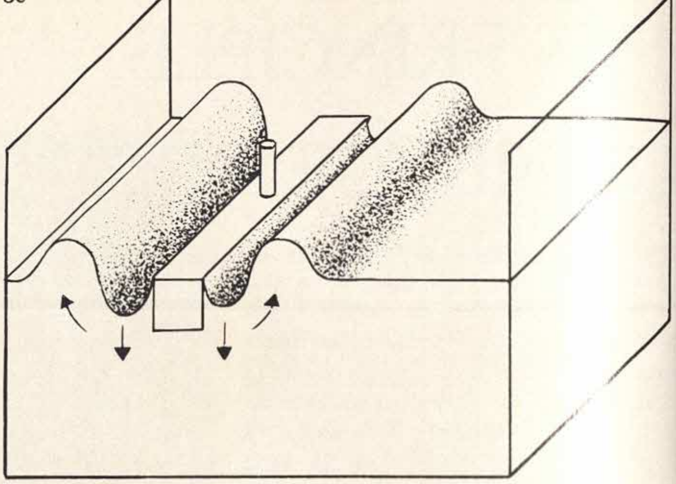

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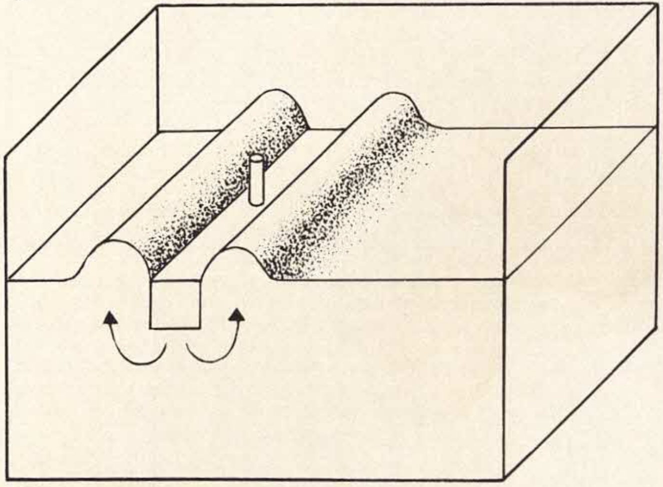
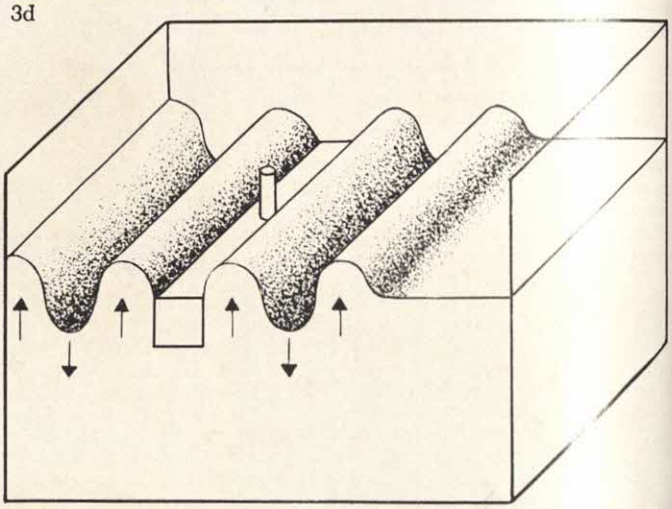


3d



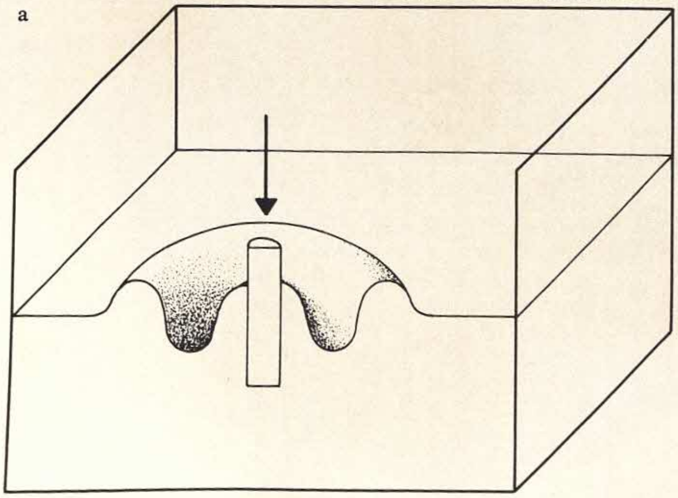
MAKING A WAVE IN WATER—In this experiment, an object shaped like that in the diagram, with a handle by which it can be moved up and down, is placed on the surface of the water (Illustration 3a) so that its lower surface is barely wetted. Now the object is immersed in the water (Illustration 3b) to a depth about equal to its height, displacing on each side a volume of water equal to its own volume. If the immersion is made very rapidly, the water will heap up on the sides in such a way that the immersed object will be momentarily flanked by two walls of water.

The water that has formed these walls is in an unstable position, and will tend to fall back in the direction indicated by the arrows (Illustration 3c), and through inertia will continue to descend even below the flat surface of the remainder of the water. In so doing, it will displace more water on the side further away from the solid object, and this water will in turn be forced to rise. As the motion continues (Illustration 3d), the water that rose will descend and thereby raise water that previously lay in front of the wave front. In fact, the up-and-down motion of the particles of water—even the smallest particles, the molecules—is responsible for the motion of all adjacent water particles.

4

MULTIPLE WAVE FRONTS—If, instead of one elongated prism, as in the previous experiment, a small cylinder had been immersed in the water (Illustration 4a), a concentric series of circular waves could have been made rather than rectilinear waves. Now, if several such cylinders are immersed side by side (Illustration 4b) simultaneously, circular waves will spread out from each cylinder; but at a greater distance, a continuous wave front will develop, exactly as if a long prism had been immersed. The circular waves spreading out from the individual cylinders become superposed at a certain distance, in such a way as to form waves with rectilinear crests parallel to the straight line that could be drawn along the centers of the individual cylinders.

a



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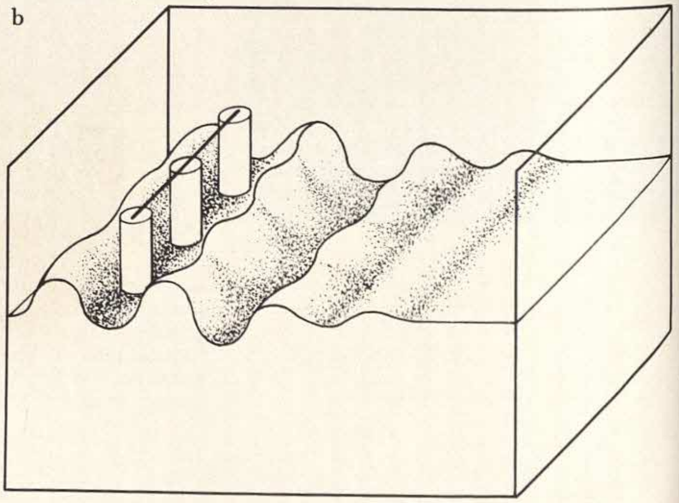

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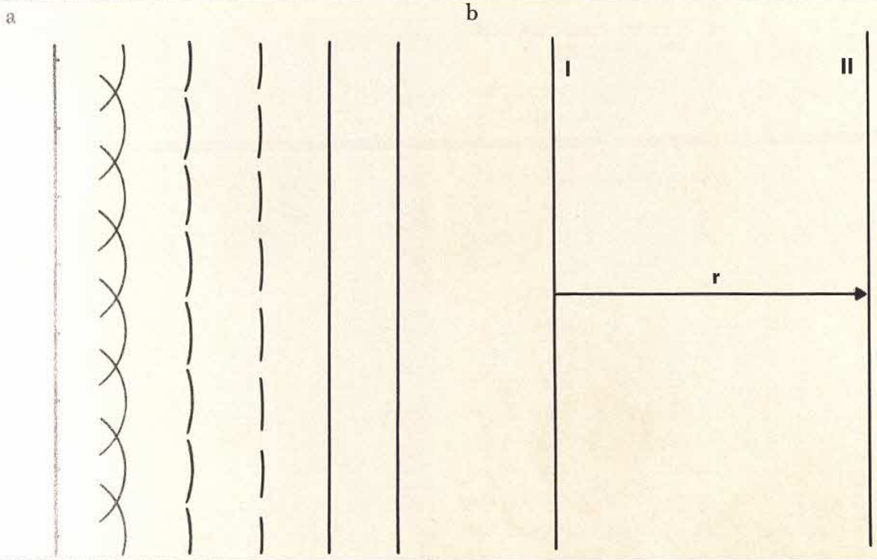
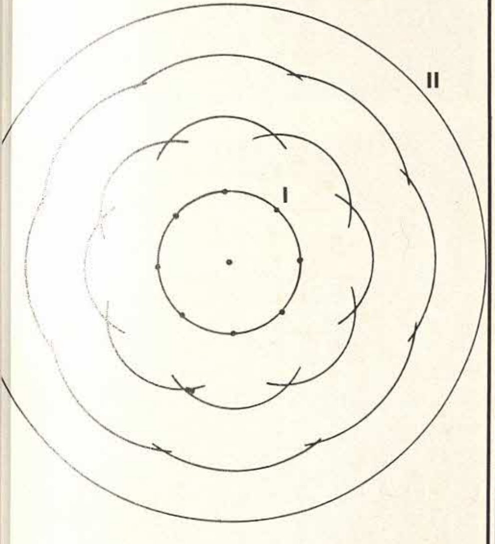


THE PRINCIPLE OF HUYGENS—According to this principle, any point on a wave front acts in such a manner as to create a circular wave around itself; and at a certain distance all the waves so created combine to form a single front (Illustration 5a). Once the form of the wave front is known at a certain distance, its eventual form can always be predicted if the velocity by which the wave is propagated is also known. For example, a wave front (Illustration 5b) that is initially in position I will result in a new wave front at II because of the combination of the action of all the particles in the first wave front—just as the imaginary line through the cylinders in Illustration 4b resulted in the single long wave front at a certain distance. The direction in which the wave is propagated is represented by **r** (which would, in the case of a light wave, represent the direction of the ray). The principle of Huygens also indicates that the direction of motion of a rectilinear wave front is itself rectilinear, and perpendicular to the wave front.

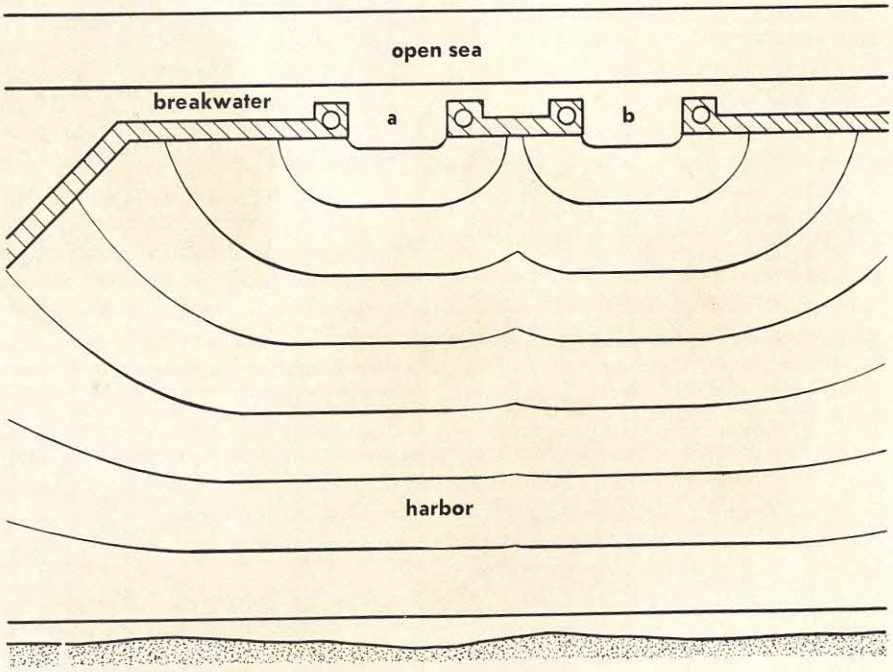
6



CIRCULAR WAVE FRONTS—The principle of Huygens can also be applied to circular wave fronts. At a certain distance, the wave front caused by the disturbances in the center reaches position I. Here, according to the principle that each point on the front creates its own circular wave front, which eventually combines to form a new single wave front, a new wave front is created further from the center, at II. The amount by which II has been enlarged as compared to I depends only on the velocity of wave propagation and the time elapsed. In the case of water waves, the velocity would be measured in feet per second; in the case of light and other electromagnetic waves, it would amount to 299,793 km per second (186,282 mi per second).

A WAVE FRONT ENTERING TWO APERTURES—This illustration shows a harbor protected from the open sea by a breakwater with two entrances **a** and **b.** When a wave front generated in the sea reaches the breakwater, the water will rise at each entrance; in descending, it will cause vertical displacements—a wave motion—within the harbor itself. In the immediate vicinity of the entrances, these waves will become circular fronts and will spread out from the centers of the two entrances. However, according to the principle of Huygens, they will eventually unite within the harbor to form a single rectilinear wave.

7



INFRARED RAYS | measurement and production

The housewife of tomorrow may well measure cooking times in seconds rather than minutes. Even now a large roast can be cooked in a few minutes rather than in hours. The secret lies in infrared rays (literally below red rays).

In 1800 the British astronomer William Herschel repeated Sir Isaac Newton's experiments in which he dispersed sunlight through a prism to produce the rainbow colors of the solar spectrum. Herschel wished to know which of the colors was most effective in heating the bulb of a thermometer. He found violet, blue, and green light quite effective, while yellow, orange, and red heated the bulb even more. To his great surprise, Herschel then discovered that the thermometer bulb was heated even further when left in the dark zone beyond the red end of the spectrum, where no light was visible. Herschel had discovered infrared rays, whose wavelengths are longer than those of visible light but shorter than those of radio waves.

Because of the limitations of the simple thermometer, there was no substantial progress in the study of infrared rays until 1830, when the Italian physicist Leopoldo Nobili turned to the thermocouple devised by the German physicist T. Seebeck a few years earlier (1821). Seebeck had found that when wires of two different metals were joined at one end and then heated, an electromotive force (emf) was produced between the other ends of the wires. Nobili placed a thermocouple in the infrared zone of the spectrum, measured with a galvanometer the weak electrical current produced, and used this measurement to determine the heat produced by the invisible rays. A few years later, the Italian physicist Macedonio Melloni went a step further by combining a number of thermocouples to create a thermopile. Melloni concluded that infrared rays possess the properties of light rays and so are of the same nature, a hypothesis already put forward by William Herschel. John Herschel, son of William, also carried out experiments that led him to the same conclusion: infrared rays and light rays are alike, with the notable exception that infrared rays cannot be seen by the human eye.

In 1847, the French physicists H. L. Fizeau and L. Foucault showed that infrared rays can produce interference phenomena, behaving as visible rays do. This confirmed the undulatory nature of infrared rays; but the scientists were not able immediately to measure the wavelength of the rays. Other scientists who tried to measure the wavelength of infrared rays concluded that the light of the sun contains not only visible light but infrared rays up to a wavelength of 1.5 microns (μm). The wavelengths of visible light rays range between 0.4 and 0.7 μm, they concluded. Thus the conviction took root that the visible rays were bordered by a certain number of infrared rays that presumably terminated just beyond the wavelength of red.

Still other experiments, in 1859, showed the existence of infrared rays up to a wavelength of 1.9 μm. The limit was soon extended to 2.14 μm, and other scientists, including Pierre Curie (who was later to become famous for his discovery of radium), brought the limit up to 7 μm. By this time the idea that there was a limit to the maximum wavelength of infrared rays had been discarded.

Today, infrared rays are produced, manipulated, and revealed readily with wavelengths of 700 to 1,000 μm, the latter equal to a millimeter in length. These modern-day experiments are carried out with techniques similar to those for optical rays, except that the equipment is specially designed to disperse, absorb, and reflect infrared rays. Electromagnetic rays extend well beyond the 1-mm wavelength. Wavelengths greater than 1 mm can be produced by special infrared sources; and rays with wavelengths of less than 1 mm are produced regularly in laboratories with instruments used in producing microwaves.

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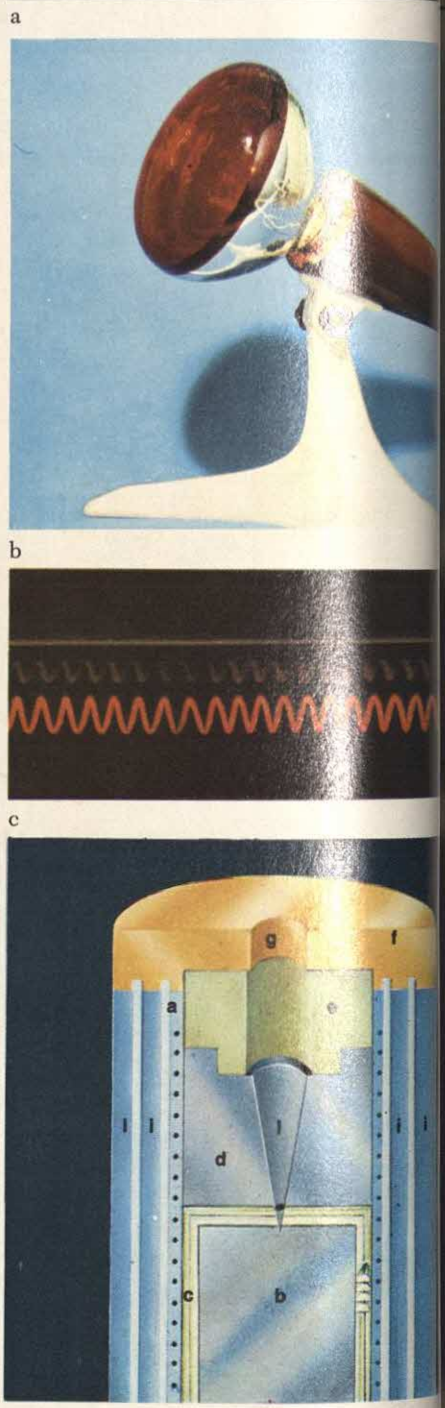
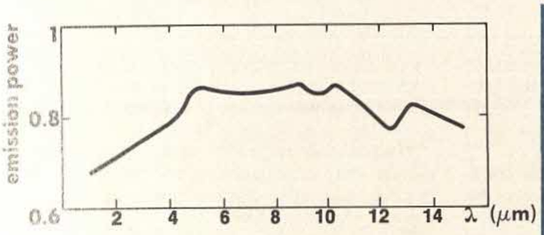


SOURCES OF INFRARED RADIATION—The sources of infrared radiation can be divided into two categories: those for technological use and those for scientific use. Nine different sources are shown in this illustration.

Illustration 1a shows an infrared lamp, consisting of a normal bulb with a tungsten filament. It is constructed in such a way that, when the appropriate current is fed in, the filament reaches a temperature of almost 1,000° C (1,832° F). The filament then gives off many more infrared rays than light rays. The light rays are eliminated by using red glass in the part of the bulb through which the rays emerge. Such infrared lamps are used for drying paint, for heat therapy, and for other purposes.

Any filament lamp can be used as a source of infrared rays; all that is needed is to feed in a lower current than that for which the lamp was designed. In this case, however, the intensity of the radiation is much less than (about one quarter) that which can be obtained with the full current.

Illustration 1b shows an infrared source used mainly for heating; it consists of a chrome-nickel coil contained in a quartz tube. When heated by electricity to a temperature of between 700 and 800° C (about 1,292 to 1,472° F), it emits a large amount of infrared rays. Both the lamp and the coil behave much like black bodies. Thus, if their temperature remains around 700 to 1,000° C (about 1,292 to 1,832° F), only a small amount of d



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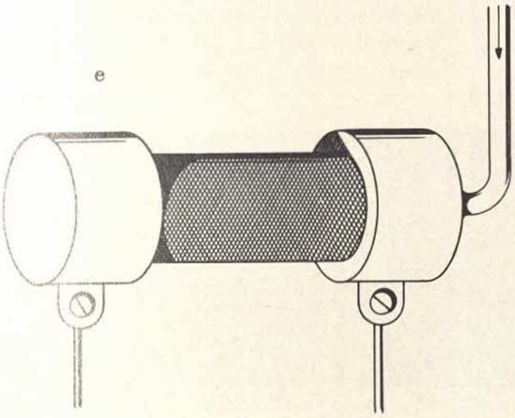

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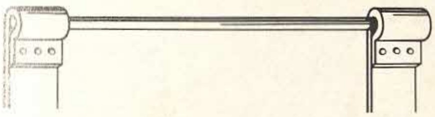

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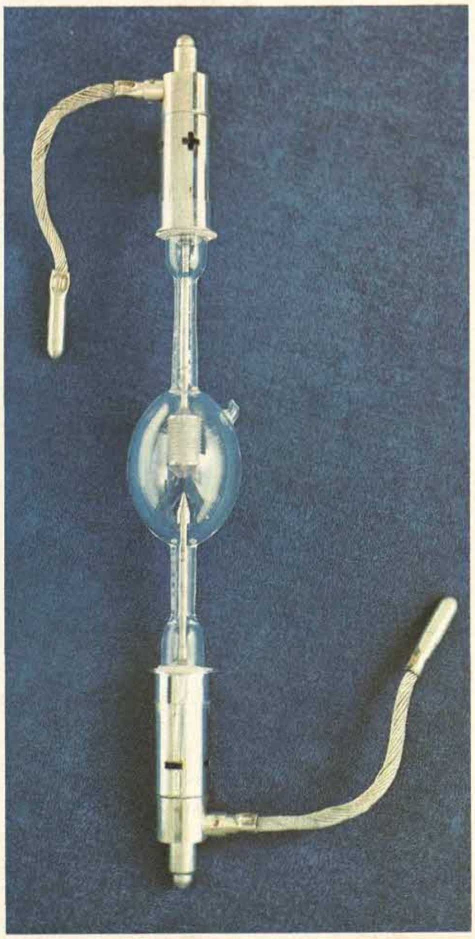

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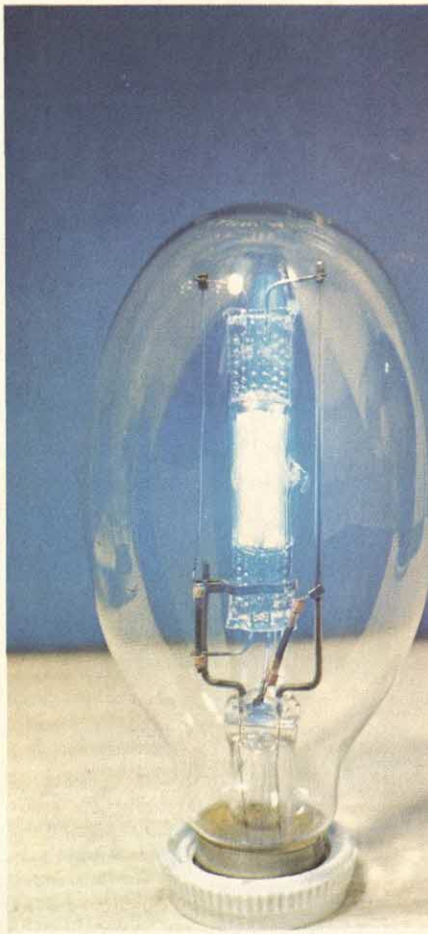


visible rays per cm² is emitted. At higher temperatures, far more visible light rays than infrared rays are emitted.

To determine how much energy is received by an infrared detector, the detector is exposed to a source that emits a known quantity of infrared rays. The source that possesses this property is the ideal black body, which consists of a box-shaped cavity with a small opening (Illustration 1c). The quantity and quality of the radiation emitted depend on the temperature of the interior of the cavity. The source consists of a cylindrical receptacle, the interior of which is heated by a chrome-nickel resistance **a.** A steel body keeps the temperature constant through its thermal inertia **b.** A quartz tube then insulates the wires of the thermopile from the steel body **c.** A metal body with a conical cavity **d** is maintained at the required temperature; an insulating material **e** separates it from the closing shield **f** through which an opening is made **g** for the radiation to emerge. The entire body of the cavity is insulated from the surrounding atmosphere by a series of concentric nickel tubes **i** polished on both the inner and outer surfaces. The heat cannot emerge except through the emission opening and the absorption of these surfaces, which have been made specular and thus minimal. The radiation detector to be calibrated, placed opposite the opening, receives a quantity of the radiation emitted that depends on the temperature reached inside the cavity (which is measured by the thermopile **l**), and on the size of the opening in the cavity.

The infrared sources shown in Illustration 1e, 1f, 1h, and 1i were designed for use in spectroscopic studies; all have elongated filaments because they are used to illuminate spectroscopic openings. The elongated shape is more economical than any other form. These sources must also be able to function in air. If the sources were contained in bulbs of glass or any other material, it would be difficult to find a material that would allow the required radiation to pass through. Almost no materials are sufficiently transparent for medium and distant infrared rays.

The graph (Illustration 1d) shows the emission curve of a Globar source, which consists of a rod of sintered silicon carbide. When heated by an electric current to no more than 1,400° C (2,552° F), the rod can be kept for several hours in air without oxidizing; it must then be replaced.

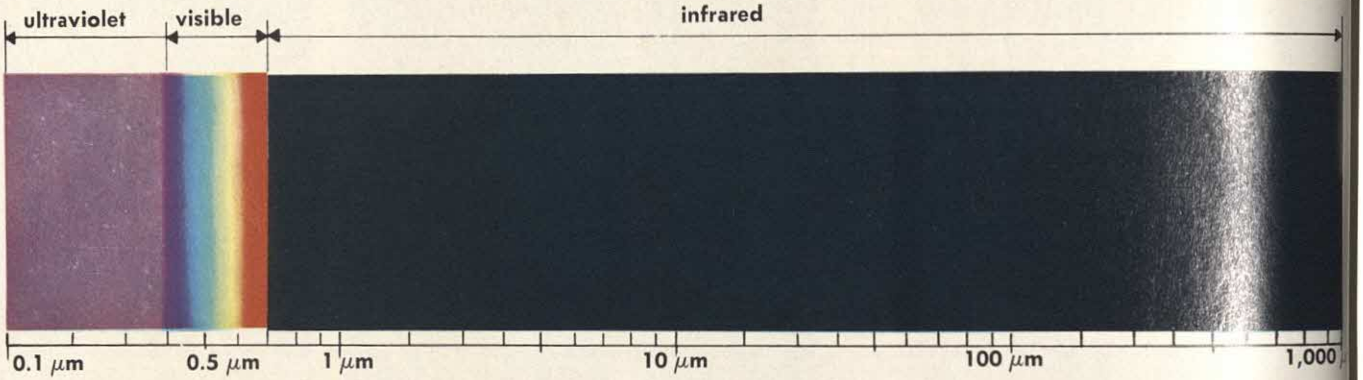
Illustration 1e shows a Welsbach mantle, which consists of a piece of wire mesh heated partly by a flame (as in miners' safety lamps) and partly by a current flowing through the mantle itself. The thorium oxide with which the wire is covered emits rays with wavelengths of from 0.6 to 6 μm.

The Nernst lamp (Illustration 1f) consists of a tube about 1 mm (about 0.039 in.) in diameter and 30 mm (about 1.18 in.) in length made of yttrium oxide and zirconium. When heated to a temperature of about 2,200° C (3,992° F), the tube emits very intense radiations.

Illustration 1g shows the flame of the voltaic arc.

The voltaic arc (Illustration 1h) is a good source of infrared rays because of its temperature and because it has the properties of a black body. It also has the property of being very brilliant, emitting a high intensity of radiation per unit area of surface.

The high-pressure mercury vapor arc (Illustration 1i) is the best source of very long infrared rays, those up to about 1 mm. In this field of radiation, quartz is very transparent and is used to screen the lamp. For wavelengths of between 10 and 100 μm, on the other hand, the best source is either the carbon arc or the Welsbach mantle.



THE INFRARED SPECTRUM—In this illustration of the spectrum, the dark area at the right is the wave band known as infrared because it appears beyond red in the rainbow of visible colors. Infrared rays range from 0.7 to beyond 1,000 μm. Because it is convenient to produce and study three qualities of infrared rays, this wave band can be divided into three regions—near, medium and distant. The properties of the rays depend solely on the difference in their wavelengths; they shade off gradually into one another. The wavelengths of near infrared rays range from 0.7 to 1.5 μm; medium, from 1.5 to 10 μm, and distant, from 10 to 1,000 μm and beyond.

Near infrared rays possess all the properties of visible light, but they cannot be perceived by the eye. They can, in practice, be produced from the same sources as are used for visible light and studied with the same detectors (photographic plates, photomultipliers, and photocells). Almost all substances transparent to light are also transparent to near infrared rays.

Medium infrared rays require different techniques for their production, detection, and application, but these techniques are no more complicated than those used for light rays.

Distant infrared rays require special instruments for production and detection.

HOW INFRARED RAYS ARE PRODUCED

There are many reasons why infrared rays are produced and studied. Infrared rays have very important practical applications and are used, for example, for drying paint, cooking food, in therapy for rheumatic and traumatic pain, and even as a means of heating specialized environments. Certain special instruments make it possible to "see" an object that would otherwise be invisible to the human eye (such as an object in darkness) by making use of the infrared rays that the object emits or reflects. Projectors that illuminate the object are necessary for this purpose.

Among the most important of the many scientific infrared applications are those that concern the study of molecular structure. Just as atoms emit visible and ultraviolet rays when they are excited by collisions, molecules emit infrared rays when they collide with one another as the result of thermal agitation. Analysis of these emissions enables scientists to determine the structure of molecules, especially those composed of many atoms.

Many molecular structures, especially those of organic molecules, have been defined through spectroscopic studies. Once the spectrum of a molecule has been identified, that spectrum can be used in analysis to discover the presence of compounds and often to regulate the concentration of compounds in solutions or preparations. Scientists produce infrared rays, pass them through the substance they wish to study, and analyze the rays with a spectrophotometer.

One of the major difficulties in producing sources of infrared rays, especially distant ones (those with wavelengths of from 10 to 1,000 μm), is that these sources behave almost like black bodies, emitting not only infrared rays but other, visible rays that may be detrimental to an experiment. (A black body is one composed of a substance, such as coal or pitch, that absorbs almost all the light falling on it and reflects very little of that light.)

One effective method of producing infrared rays is heating a black body to a high temperature. The higher the temperature, the more infrared rays are produced; however, because the source possesses the properties of a black body, the more the temperature is increased, the more the visible rays increase—and at a proportionately greater rate than that of the infrared rays. Doubling the infrared ray production increases the visible ray production tenfold. In seeking pure infrared rays for experiment, it is very difficult to eliminate the unwanted visible rays; special devices are needed to overcome the black body properties and thus produce more infrared than visible rays. It is difficult to estimate the percentage of defect and to make sure that it is the same for all wavelengths. Some allowance usually is made for incomplete absorption in modern experiments; but it remains a source of uncertainty in making accurate measurements.

ULTRAVIOLET RADIATION | sources and uses

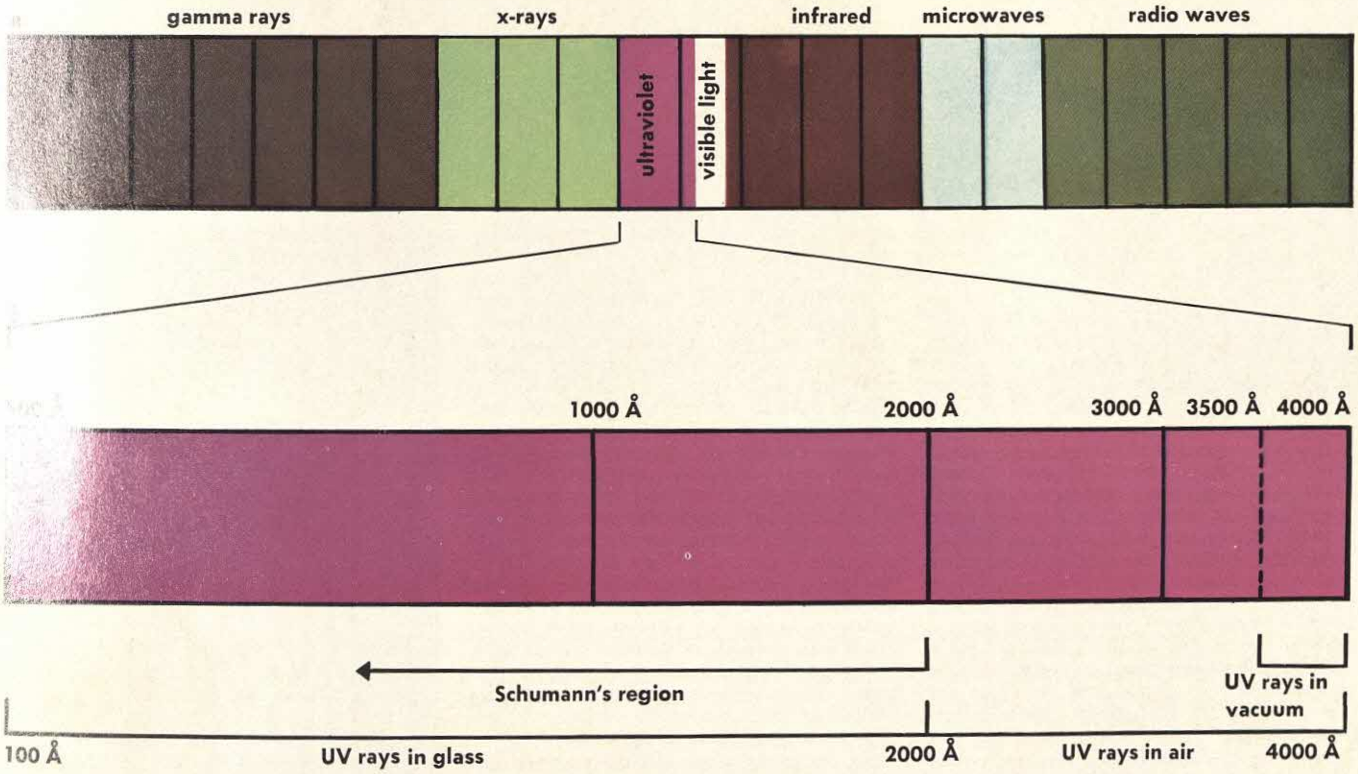
There are many reasons for the study of ultraviolet rays. Most important, ultraviolet radiation provides information about the state of matter. For example, such radiation emitted by the sun or any other star indicates that the star's atmosphere is composed of very hot gas. From the quantity and wavelengths of the radiation emitted, the physical conditions of the star's atmosphere can be determined.

Ultraviolet rays help reveal the structure of matter in the solid state. Such rays emitted by an atom indicate not only the energy level of its electrons but how the electrons are arranged around the nucleus of the atom. Just as infrared rays serve in the investigation of molecular structures, so ultraviolet rays serve in the study of atomic structures.

A practical application of ultraviolet radiation is based on the fact that many organic substances do not transmit radiation of certain wavelengths; instead the radiation is absorbed. The specific absorption characteristics of many organic substances are determined by use of a spectrophotometer.

PROPERTIES OF ULTRAVIOLET RADIATION

The subdivision of electromagnetic radi-



THE SUBDIVISION OF ULTRAVIOLET RAYS —Drawn to logarithmic scale, Illustration 1a shows the complete spectrum of electromagnetic radiations. Ultraviolet rays have a shorter wavelength than that of visible light.

Illustration 1b shows the subdivisions of the ultraviolet wavelengths. Broadly speaking, these subdivisions are made up of near and distant ultraviolet rays, with an intermediary region. While such subdivisions are somewhat arbitrary, they are often used in textbooks, and are identified by the terms given below.

1. *The wavelengths of ultraviolet rays through glass.* Ultraviolet rays between 4,000 and about 3,500 Å can penetrate ordinary glass (but not lead glass), providing the glass is no more than about 1 cm (about 0.4 in.) thick.

2. *The wavelengths of ultraviolet rays through air.* Air is transparent to ultraviolet rays at 2,000 Å, but is opaque to shorter wavelengths. Thus it is customary to speak of the region between 3,500 and 2,000 Å as that of ultraviolet rays in air.

3. *The wavelengths of ultraviolet rays through a vacuum.* Because air is opaque to ultraviolet rays below 2,000 Å, such radiation must be studied in a vacuum.

4. *Schumann's region.* Extending from 2,000 Å to a few hundred Å, this region of wavelengths is named for the physicist who studied it and who discovered a photographic process for revealing its radiations.

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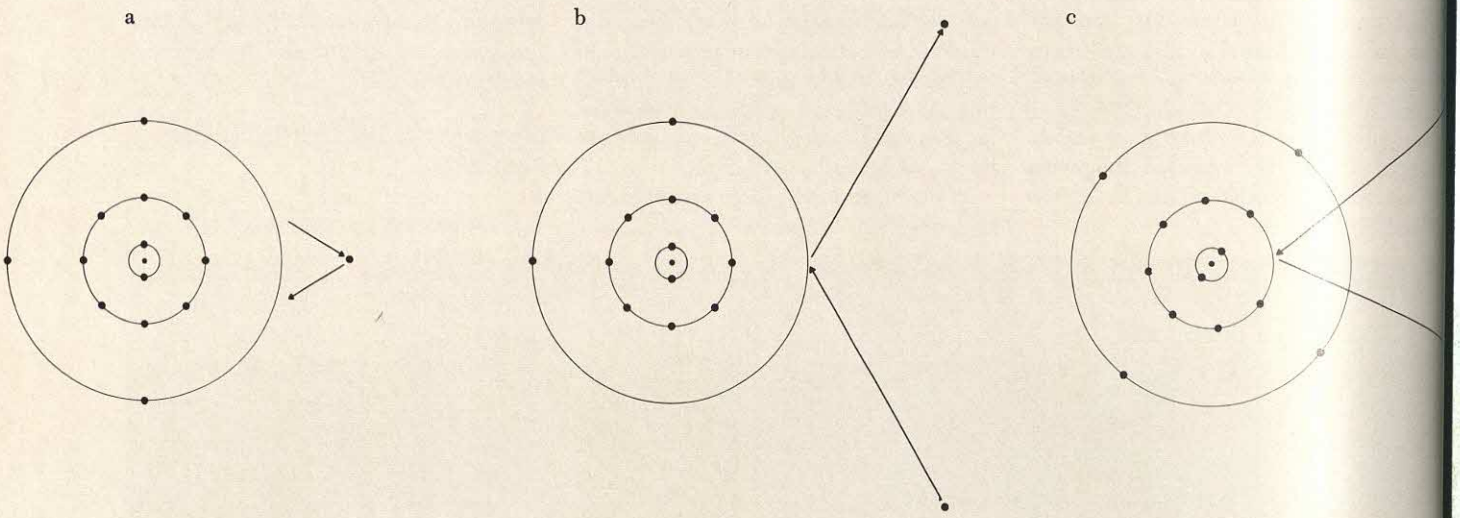

d

THE ORIGIN OF ULTRAVIOLET RADIATION— Ultraviolet radiation results from the loss of energy by electrons. When an electron is bound to an atom, it can be made to generate radiations on a single or a finite number of wavelengths. On the other hand, a free electron (one not bound to an atom) can generate radiations of any wavelength. The simplified atomic model shown illustrates these facts.

The distances of the electrons from the nucleus of this atom (Illustration 2a) determine the amount of energy each electron possesses. When one of the electrons is displaced a short distance away from its orbit, it soon falls back, emitting electromagnetic radiation. According to quantum mechanics, a clearly defined quantity of energy having an exact value must be applied to displace the electron from its orbit. When such a displaced electron returns to its orbit, this energy is liberated. Because both the energy applied and that relative to the orbit to which the electron belongs are definite, the atom will emit radiation of this energy whenever the electron is displaced. Thus, while an atom can emit different wavelengths, corresponding to the various possible displacements of its electrons, the values of these emissions will always be clearly defined and discrete.

When an atom loses an electron, a state of ionization occurs (Illustration 2b). A radiation with a precise wavelength can still be obtained in such a state by applying a clearly defined quantity of energy with an exact value, as described for Illustration 2a. When ionization occurs, the remaining electrons become more closely bound to the nucleus. If another electron is then removed from the nucleus, it may, upon its return, resume its former position; or, it may take over the position of the first electron removed. In either case, the radiation emitted will be different. In the first case, the radiation will be in the ultraviolet range; in the second, the radiation will be in the range of visible light rays.

When an electron is removed from one of the more internal orbits and replaced by another electron (Illustration 2c) the radiation produced is an x-ray. Thus ultraviolet radiation is that emitted by the more external electrons of an atom. These external electrons are known as optical, or valence, electrons because they are responsible for the association phenomena of atoms in molecules, and because visible electromagnetic radiations are emitted as the result of the variations of energy possessed by these electrons.

An electron violently projected against an atom and then deflected as a result of the impact emits a radiation that may be ultraviolet (Illustration 2d). If the shock of the electron hitting the atom is repeated, a succession of ultraviolet emissions of wavelengths of varying values may be obtained. This phenomenon may take place in a gas, in which case the resulting radiation is continuous. This is the radiation that is emitted by a plasma, that is, a gas completely ionized and kept at a high temperature.

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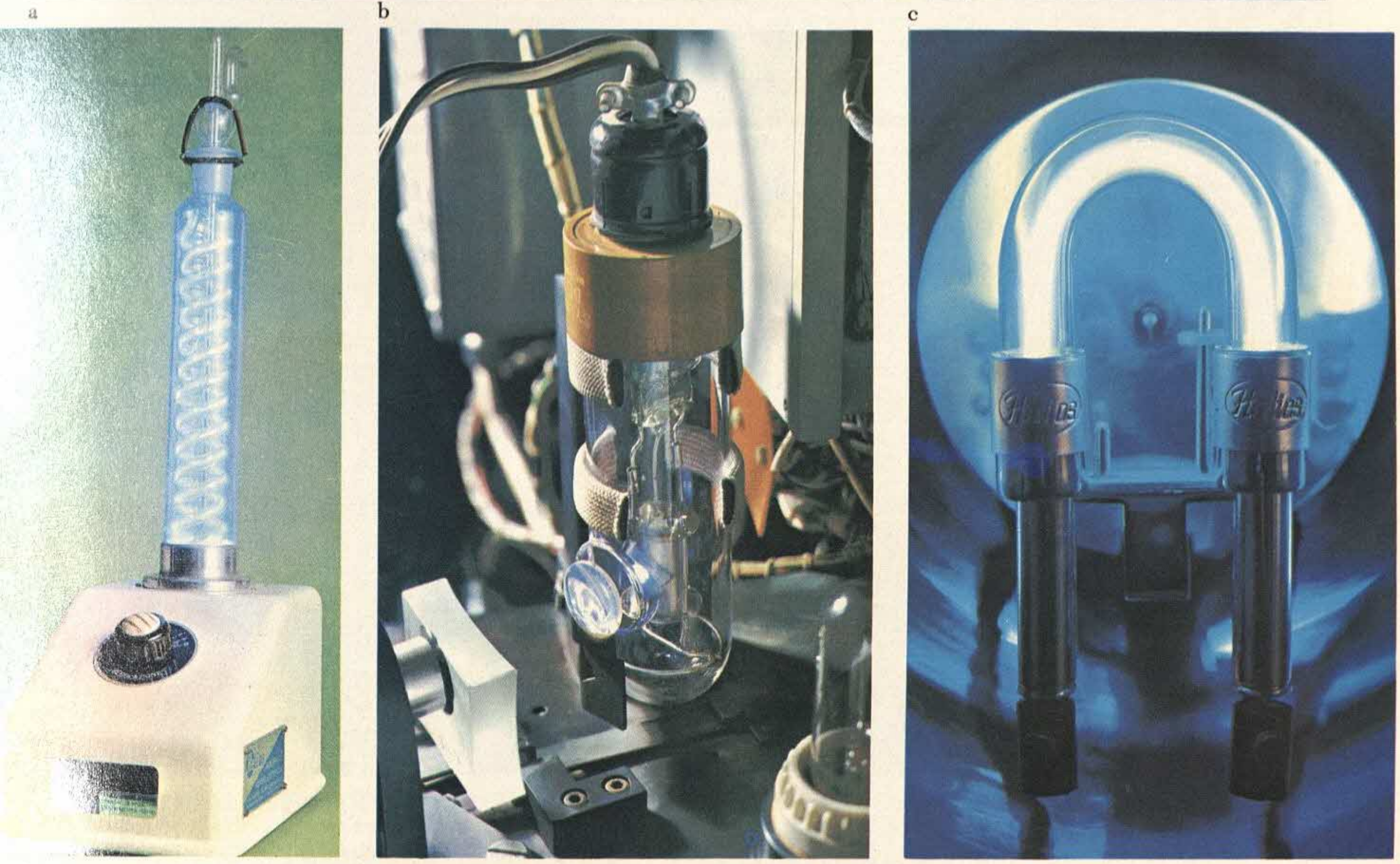

SOURCES OF ULTRAVIOLET RADIATION—The method of creating ultraviolet radiation is by producing an electric discharge in a rarefied gas. In mercury vapor, a discharge produces emission of a few distinct wavelengths; in hydrogen, a discharge produces a continuous field of wavelengths. Illustration 3a shows a mercury vapor lamp in which the discharge produces a high density of emission of ultraviolet rays. Because the rays they produce are effective germ killers, such lamps are widely used in operating rooms and elsewhere in hospitals. Illustration 3b shows a hydrogen lamp used in spectrophotometers. The gas excited by the electric discharge emits rays down to about 2,500 Å as well as rays of shorter wavelengths. However, the quartz of which the shell is made cannot be penetrated by these shorter-wavelength rays. Illustration 3c shows a lamp containing high-pressure mercury vapor, which emits intense and continuous ultraviolet rays. "Suntan" lamps are of this type. Other ultraviolet sources are the voltaic arc (flame) and the high-pressure xenon arc. Similar devices are used for the production of infrared rays. Relative to visible light, infrared rays are near the longer wavelengths.

ations into gamma rays; x-rays; ultraviolet rays; visible, or light, rays; infrared rays; microwaves; and radio waves is somewhat arbitrary. Gamma rays have the shortest wavelengths. Infrared rays extend from a wavelength of 1 μm (micron) to 1,000 μm, much longer wavelengths than those of visible rays. Ultraviolet rays extend from a wavelength of 0.4 μm to about 0.01 μm–from 4,000 to 100 Å (Ångstrom units). Relative to visible light, infrared rays are near the longer wavelengths; ultraviolet rays are near the shorter wavelengths. Gamma and x-rays have wavelengths even shorter than ultraviolet rays, while microwaves and radio waves have wavelengths longer than infrared rays.

PERCEPTION OF ULTRAVIOLET RAYS

While the eyes of some animals are sensitive to part of the ultraviolet region, those of man are barely so. Generally, the human eye is insensitive to radiations of less than 4,000 Å. At 4,000 Å, the human eye is unable to perceive objects in focus. Observing a subject through a filter that passes only those rays on the border between visible and ultraviolet, the eye reacts as if shortsighted. The cause of this reaction is that the crystalline lens of the eye has a much shorter focal length for violet than for the other colors of the visible spectrum.

Proceeding from the visible to shorter wavelengths at about 3,600 Å, the eye perceives a violet color that gradually fades into gray. Below 3,600 Å, a radical change occurs: the retina is no longer sensitive to radiations, and the aqueous humor becomes fluorescent. A person whose eye has been illuminated with ultraviolet rays on wavelengths between 3,500 and 2,500 Å experiences a sensation akin to a lamp bulb being lit inside his eye. The retina receives the impression of light but is unable to distinguish a source, because the whole of the retina is illuminated equally. This phenomenon is impossible to create by illumination of the eye with visible light and is thus in the category of an interesting scientific curiosity.

X-RAYS | revealing the mysteries of matter

When fame came to Wilhelm Conrad Röntgen, it came with a rush. In 1895 Röntgen was fifty years old and a relatively unknown professor of physics at the University of Würzburg, Germany. Six years later he was a Nobel laureate—winner of the highest prize in physics. Röntgen had been experimenting on the conduction of electricity through gases, using a highly exhausted vacuum tube, when he accidentally discovered that a mysterious, invisible radiation from the tube caused a little barium platinocyanide screen to become luminescent. The rays, he found soon after, had the power to pass through materials that were opaque to ordinary light. Röntgen, who called this radiation x-rays (x for unknown), went on to amass much of the early information about the properties of the rays.

Studies determined that x-rays were wave-like, behaving in many ways like visible light rays, but with a greater ability to penetrate matter than any other rays known. Initially, Röntgen reported that x-rays could not be reflected or refracted—they just seemed to travel on in a straight line through materials that did not absorb them. This would have constituted a marked difference from light rays, which tend to bounce off or change direction whenever they enter a different material. Eventually, reflection by metal mirrors was shown at very small grazing angles, that is, when the rays struck the mirror in such a way that the beam was almost parallel with the surface of the mirror.

In 1906 another kind of reflection was shown, the so-called scattering of x-rays. Although the wavelengths of x-rays are so small that most of them pass straight through the spaces between atoms, some rays may be bounced off in random directions by collision with electrons in the shells of the atoms. By counting the scattered rays, researchers in 1906 correctly determined the number of electrons in the carbon atom as six.

In proving the wave-character of x-rays, the apparent absence of refraction was a major difficulty, for the wavelengths of electromagnetic rays (radiation similar to light) are commonly computed from the changes in direction when rays enter different materials or pass through narrow gratings or slits. The width of the slit, together with the width of the wave (wavelength) determines the amount of direction change. In 1902 a slit was made narrow enough to slightly broaden an x-ray beam. An average wavelength of about 0.4×10^{-8} cm (0.4 Å) was determined in that way (10^{-8} cm $= 10^{-10}$ meter $= 1/10^{10}$ meter = one ten-billionth of a meter = one Ångstrom unit = 1 Å). Later, the x-ray spectrum was found to run from wavelengths of around 100 Å to very short wavelengths on the order of 0.01 Å and beyond. The shorter the wavelengths, the higher the frequencies, and the more penetrating, or "harder" the x-rays. The x-ray wavelengths were much shorter than those of light and ultraviolet rays.

The change of direction resulting from the passage of a ray through a narrow slit or grate is called diffraction. Since many crystals may be considered as patterns of atoms regularly arranged in parallel planes with equal distances between them, x-rays could be diffracted by crystals, and the patterns of crystal diffraction established the structures of the various crystals.

The principal means of producing x-rays remained the vacuum tube, such as Röntgen had used. If a high voltage is applied to the electrodes of the tube, a stream of electrons shoots from the negative electrode (cathode) through the vacuum toward the positive electrode (anode). When the electrons, also called cathode rays, strike a solid, they lose energy in x-rays and so excite electrons in the atoms of the solid, which in turn radiate energy in the form of x-rays. The higher the voltage applied, the "harder" the x-rays are.

The wavelength patterns, or line-spectra, of the x-rays are different, according to the different chemical elements that are made to radiate by electron bombardment. In 1914 it was shown that there was a direct mathematical relation between these wavelength patterns and the atomic numbers (corresponding to the numbers of electrons in the atomic shells) of the different elements. This discovery afforded a confirmation of the

THE RANGE OF X-RAYS—Exact limits cannot be established for the range of wavelengths that correspond to a given type of radiation. According to Illustration 1, x-rays have wavelengths between 0.01 and 100 Å. (1 Å, or Angstrom, is one ten-billionth of a meter. X-rays with wavelengths outside these limits indicated do exist, however. The properties of x-rays as they relate to matter vary considerably, depending on their wavelengths.

The simplest variable characteristic of x-rays is their power to penetrate. X-rays on wavelengths between 0.01 and 0.5 Å, which can penetrate into condensed substances to a depth of many centimeters, are known as penetrating or hard x-rays. Those on longer wavelengths, up to the extreme limit, are blocked by thin layers of material—a few thousandths of a millimeter of metal or a few centimeters of air—and are known as soft x-rays.

All the wavelengths included in the range discussed here are those of x-rays that can be produced by either the deceleration of free electrons or variations in the energy level of the electrons in the atom, usually those electrons that are nearest the nucleus and that contain a higher binding energy.

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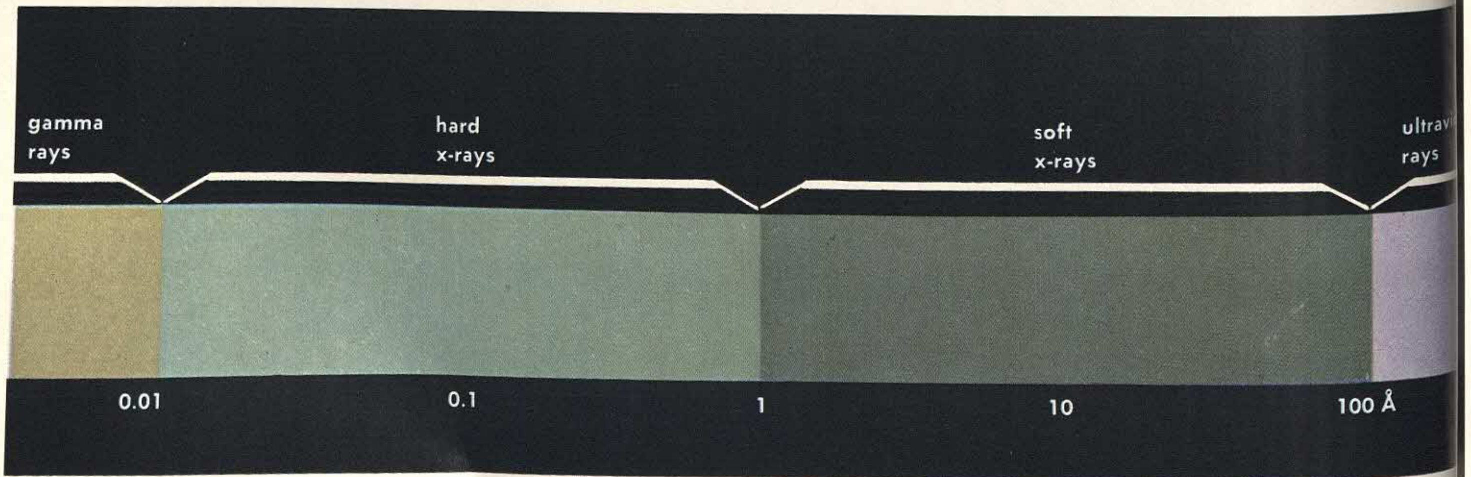

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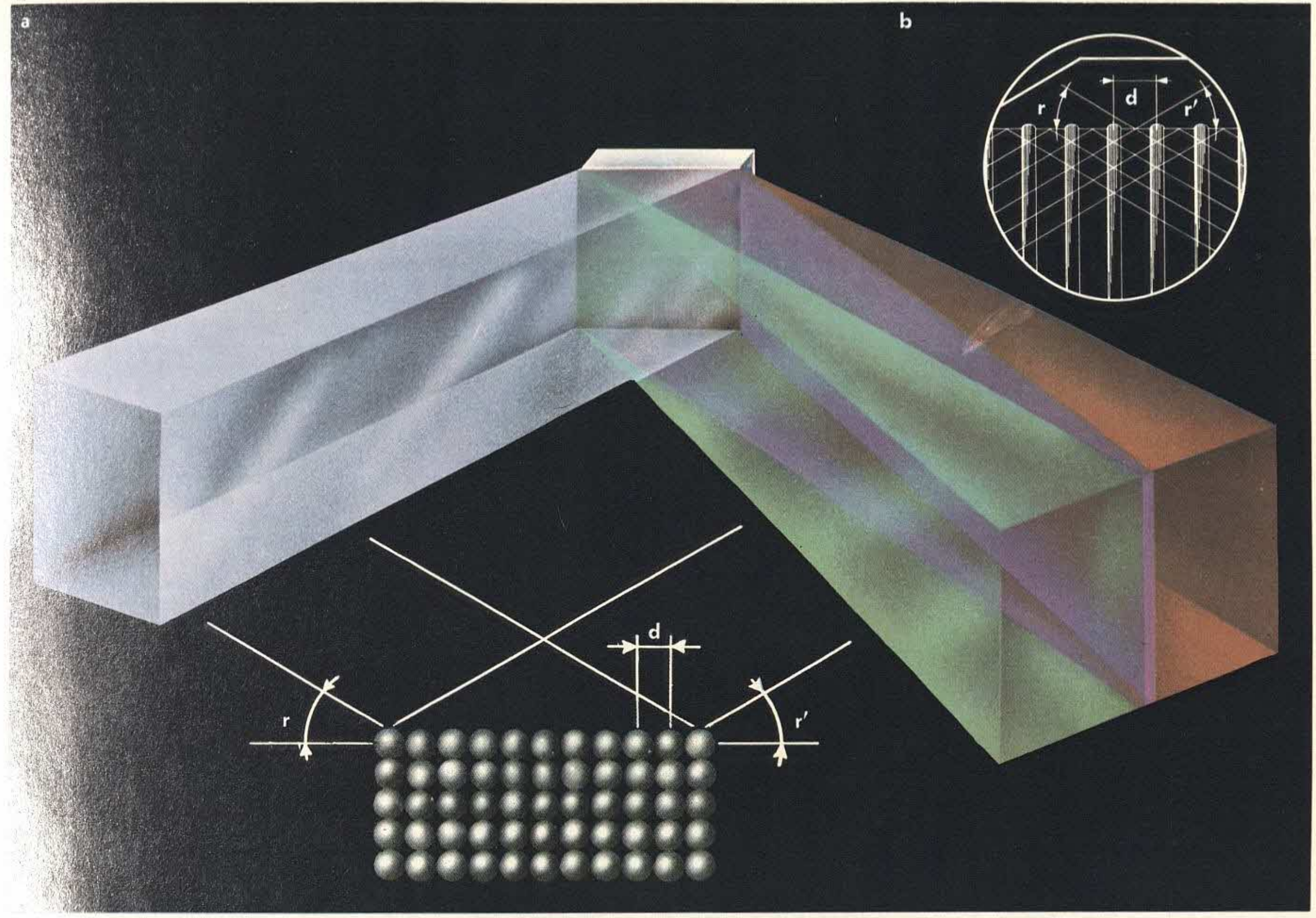

THE UNIT OF MEASUREMENT FOR WAVELENGTHS—Scientists usually measure length in units that are multiples or submultiples of the meter. The wavelengths of visible light, ultraviolet rays, and x-rays are measured in Angstroms. Earlier, however, scientists found it necessary to introduce a new and slightly different unit of measurement for x-rays.

Wavelengths of visible or ultraviolet radiations are difficult to measure because the distances involved are very small—less than a thousandth of a millimeter. This difficulty can be overcome by exploiting the phenomena of diffraction and interference, as shown in Illustration 2a. A beam of rays strikes an artificially ruled reflecting diffraction grating (Illustration 2b). The reflected radiation is diffracted in all directions, constructive interference taking place only in certain directions. These directions are included within the angles **r** and **r'**. If the size of these angles and the distance **d** between two successive slits on the grating are known, it is possible to deduce the wavelength of the radiation. Although this is a complicated and indirect measurement, it is based on the determination of macroscopic distances that can be compared directly with the standard meter.

A similar measurement of x-rays can be made by projecting a beam of these radiations onto a crystal of simple structure—the lattice of a cube of rock salt, for example. For a long time after the discovery of x-rays, rock salt was used as a diffraction grating because in order to repeat the procedure described in Illustration 2a, the interval **d** must be slightly longer than the wavelength to be measured. Natural gratings—crystals—must be used because the wavelengths of x-rays are thousands of times shorter than those of visible light, and because it is impossible to rule gratings with intervals thousands of times shorter than those used for visible rays. However, the intervals between these very fine natural gratings were known only through imperfect knowledge of Avogadro's constant, and all early measurements of x-ray wavelengths were worked out with a unit of measure that was not quite a submultiple of a meter. Then, scientists agreed that the constant of the grating of rock salt should be 2,814 units, each equal to .0001 Å. These units were called XU units. Large numbers of x-ray wavelengths were worked out by using the grating of rock salt, and full tables were compiled. Finally, it became possible to measure the wavelengths of x-rays by using an artificial grating. This grating was so fine that the reflection of the rays striking it was almost radiant, creating a more effective phenomenon of interference. Scientists then discovered that 1,000 XU was not exactly equal to 1 Å, but to 1.00202 Å. Today, data on x-rays are given both in Ångstroms, according to the modern practice, or in KXU (KXU meaning 1,000 XU).

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model of atomic structure that had been proposed by the Danish physicist Niels Bohr in 1913 and is generally accepted today.

So the discovery of x-rays generated many other discoveries that heralded the atomic era of physics. Besides theoretical applications, x-rays found many practical uses. Because they can be recorded on photographic plates or on screens of luminescent material, they enable man to see inside the human body. X-ray photography is an important diagnostic aid in medicine, and x-rays are also used in radiation therapy. Hard x-rays will even penetrate metal castings and welds and are used to detect flaws in them. Fine-grain x-ray photographs may be enlarged as much as 800 times with perfect resolution, and even higher magnifications of x-ray pictures can be obtained by other means. These applications in microradiography enable man to examine minute details of cell structure.

In the 1960s, x-ray science encompassed a growing number of categories. With the exception of x-ray therapy, all had industrial applications.

Certain celestial bodies, such as the sun, some nebulas, and quasi-stellar sources, emit x-rays. Interpretation of the causes of these emissions has expanded our knowledge of the nature and composition of the universe. Because x-rays are largely absorbed as they pass through the atmosphere, detection instruments must be sent into space beyond the atmosphere to enable scientists to study these rays effectively. A whole new technology of space instruments to detect x-rays has rapidly been developed.

3

TWO WAYS OF PRODUCING X-RAYS—Two different phenomena produce x-rays. One involves the slowing down of charged particles in rapid motion; the other occurs inside atoms and concerns those electrons that are most tightly bound to the nucleus.

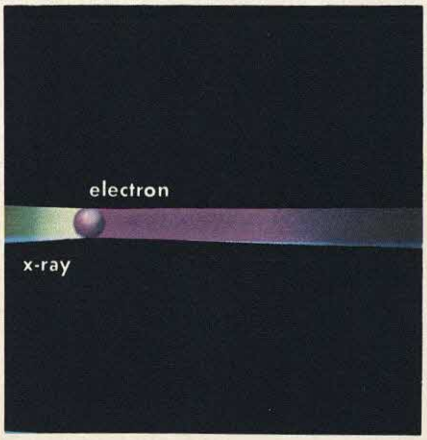
One of the laws of electrodynamics states that if no forces (such as a magnetic field) are acting on it, a charged particle in motion in a vacuum moves along a straight line and conserves its energy. If this particle collides with an obstacle, if it is accelerated or slowed down, or if its path is deviated by a force field, part of the energy of the particle is transformed into electromagnetic rays—more exactly, into quanta of radiation. The wavelength of the radiation emitted depends on the amount of energy lost by the particle; the more energy lost, the higher the frequency of the radiation emitted (and the shorter its wavelength). If the electron loses a sufficient amount of energy, x-rays are emitted. The hardness of the rays depends on the amount of energy lost by the electron. An electron free to move in space—such as one accelerated by an electron gun or other type of accelerator—may attain any value of kinetic energy and, during deceleration, lose any value less than that it has attained. X-rays can be emitted on all frequencies (and wavelengths). Illustration 3a shows an electron emitting x-rays as the result of deceleration. Such rays are known as braking rays, for which the term "bremsstrahlung" (from the German) is often used.

If a number of electrons, each with a different amount of energy, are slowed down, an x-ray (Illustration 3b) containing all the wavelengths within a certain range of frequencies will result. Braking can be caused simply as the result of the electrons colliding with a solid body. This type of radiation is termed "white" or "continuous."

The electrons of an atom, bound to the nucleus by electrostatic forces, rotate around the nucleus on orbits of different diameters. The atom model in Illustration 3c is approximate, but effective for understanding how an atom can emit x-rays. The electrons are on different orbits; those on orbits of the smallest diameters are most tightly bound to the nucleus. If one of these electrons is removed, the atom is left in an unstable state. Another electron, previously free on an orbit of greater diameter, rapidly takes the place of the departed electron. During this process energy is released and leaves the atom in the form of x-rays. The frequency and wavelength of these rays depend on the atomic structure, the position from which the free electron came, or the position of the bound electron that has been replaced.

All the atoms of the same element emit x-rays on the same wavelengths when the electron closest to the nucleus is extracted. The atoms may emit x-rays of more than one wavelength, but the wavelengths, however numerous, have distinct and well-defined values, not all the values in a certain frequency interval, as is the case with braking (white) radiation. Illustration 3d shows the frequencies emitted by a typical atom; the emission spectrum is known as a monochromatic radiation because it has well-defined wavelengths.

a



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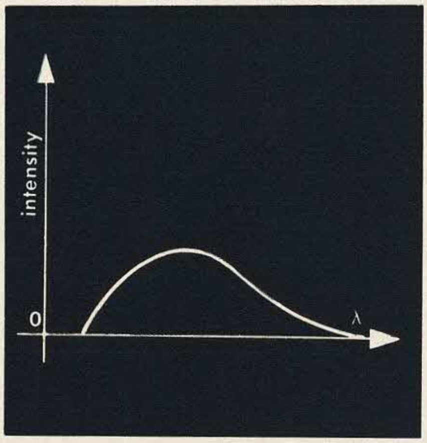
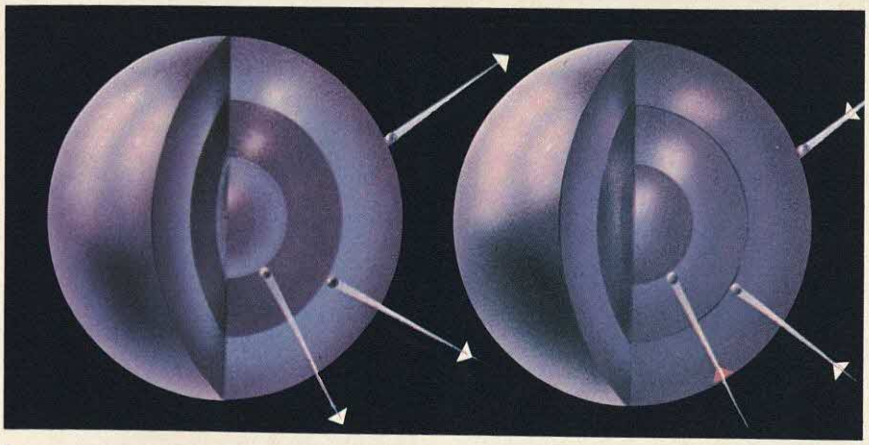
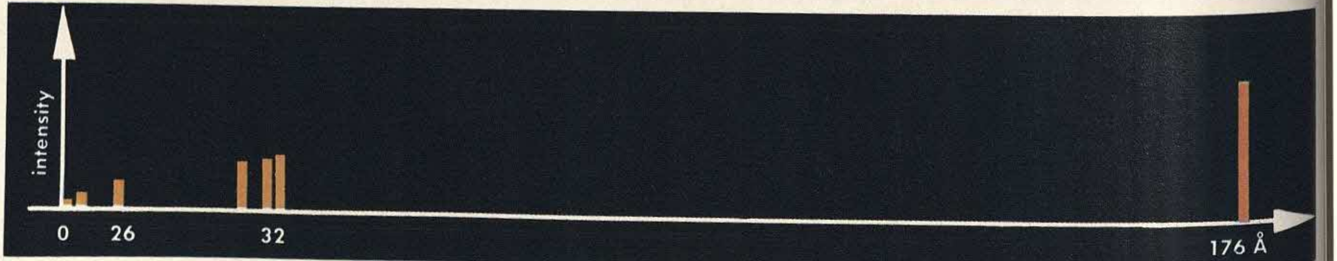


c

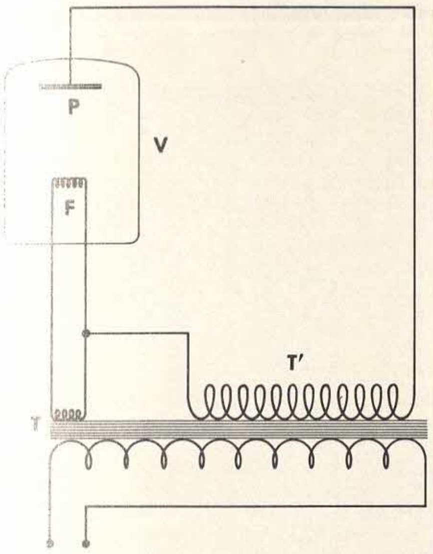


d



X-RAY SOURCES | methods of production

1



THE WORKING PRINCIPLE OF THE X-RAY TUBE—Illustration 1 represents an ordinary thermionic tube (diode) and its electric supply system. The apparatus consists of a glass bulb V with a tungsten filament **F** inside it. The filament is heated to incandescence by the current from a transformer **T.** The incandescent filament emits electrons that would be dispersed into space were it not for the metal plate **P** opposite the filament. This plate is connected to a source of alternating current, converted into high voltage by another transformer **T'**. An alternating current is set up between the filament and plate, alternately charging the plate positively and negatively. When the plate is negative, it repels electrons, which are also negative; when it is positive, it attracts them. Accelerated by the difference in potential created by the transformer, the electrons rush toward the plate when it is positive. When they strike the plate, they are braked abruptly and emit x-rays. This is the working principle of the x-ray tube, which differs from an ordinary thermionic tube chiefly in its high-voltage input. A thermionic tube has a current between filament and plate of a few hundred volts (or a few thousand at most), with the result that it does not emit hard x-rays, only ultraviolet radiations of short wavelengths, or soft x-rays. An x-ray tube, on the other hand, requires tens or hundreds of thousands of volts, and its construction is, therefore, much more complex than that of a thermionic tube.

THE RADIATION EMITTED BY AN X-RAY TUBE—An x-ray tube emits radiations in two ways: by the braking of electrons and by fluorescence. Braking radiation is produced when electrons bombard the anode and are abruptly halted. Although all the electrons arriving at the anode have the same amount of energy (because they are accelerated by the same voltage), the braking may take place in one phase or in several phases. In the latter case the electrons cause emission of x-rays whose energies are less than the kinetic energy of the electrons. This means that braking radiation may produce rays on all possible wavelengths, from the limit of the ultraviolet to a certain minimum that is determined by the kinetic energy of the bombarding electrons. The wavelength depends on the total energy of the electrons striking the anode. X-rays thus produced may reach the exterior of the tube directly, or they may be scattered by the material of the anode before emerging from the tube. Another possibility is that the x-rays may be absorbed by the atoms and cause the emission of an electron that was strongly bound to the nucleus. In this case, the place of the emitted electron is taken by another electron farther from the nucleus, thus restoring atomic equilibrium. The result of this is the emission of another x-ray with a clearly defined wavelength characteristic of the substance of which the anode is made. X-rays produced in this way are called fluorescent x-rays.

The graph shows the curve of the radiation spectrum of an x-ray tube. The lower scale shows wavelengths; the scale at the left shows the corresponding intensities of the wavelengths. The spectrum of the radiation emitted consists of a continuous curve **c** surmounted by two peaks K_1 and K_2 (fluorescent radiation). On the side of the short wavelengths, or hard x-rays, the curve ends abruptly at a clearly defined wavelength corresponding to the radiations produced by the electrons that have lost in a single phase all the kinetic energy acquired during acceleration. The relation between the wavelength of this extreme radiation and the voltage with which the electrons are accelerated can be expressed:

$$\begin{array}{c}\text{wave-}\\\text{length}\\\lambda\ (\text{Å})\end{array} = 12{,}340\,\frac{\text{joules}\cdot\text{m}}{\text{coulombs}}\ \begin{array}{c}\text{accelerating}\\\text{voltage}\\\text{(volts).}\end{array}$$

This is derived from quantum mechanics: $h\nu = eV$, or
$hc/\lambda = eV$, and thus:

$$\lambda(\text{Å}) = \frac{hc}{eV} = \frac{12{,}340}{V},$$

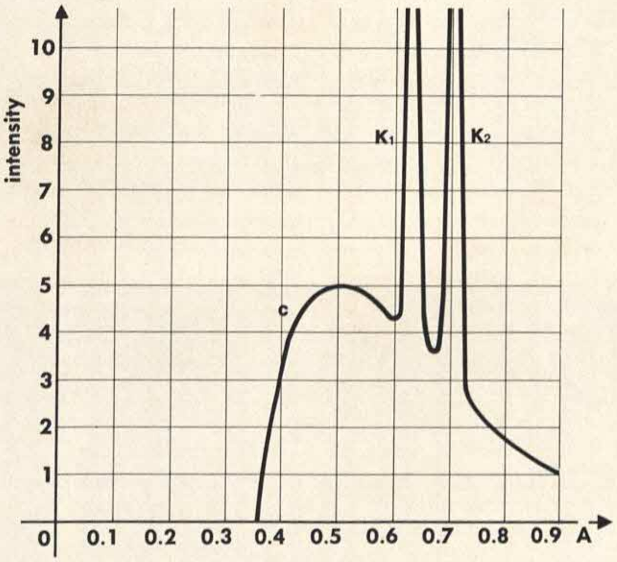
where V is volts, h is Planck's constant (6.625×10^{-27} erg sec), ν is frequency, e is energy, λ is wavelength, c is the velocity of light.

If, then, the tube is fed with 123,400 v, the x-rays produced will have a minimum wavelength of 0.1 Å. The most frequent radiation usually has a wavelength about 1.5 times greater than 0.1 Å.

Monochromatic peaks such as K_1 and K_2 exist only when the continuous radiation contains wavelengths short enough to excite the atoms.

If the filament of the cathode of an x-ray tube is intensely heated, a very intense radiation is obtained. High acceleration voltage produces hard and penetrating x-rays.

2

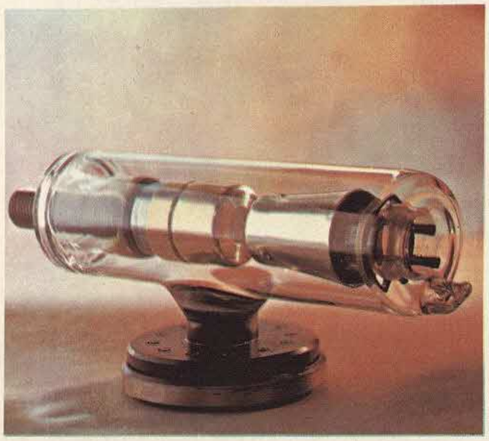


SPECIAL PURPOSE TUBES—Illustration 3a shows a tube used to produce soft x-rays—those with the longest wavelengths. In order to explore the properties of matter and of x-rays in the long wavelength field, special precautions are necessary because soft x-rays are easily absorbed, even by very thin layers of material. A tube made to emit x-rays having wavelengths of more than 3 to 4 Å must have a beryllium window instead of a glass one in front of the anode. Beryllium has a low atomic number, which gives it a high transparency to x-rays. X-rays with a wavelength as long as 10 Å are very easily absorbed, even by air. Experiments on these rays must be conducted in a vacuum. Illustration 3b is an enlarged detail of the beryllium window set into the tube.

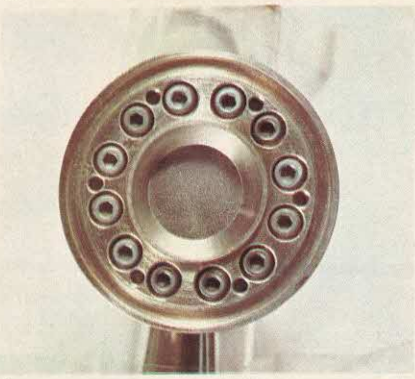
A microfocal tube (Illustration 3c) produces a pinpoint source of x-rays. Theoretically, it should be simple to produce such a source by causing the electron beam to converge on a very small area of the anode. In practice, however, the concentration of the electrons and the intense heat developed at their point of arrival cause the anode, and especially the target metal, to melt rapidly. The distortion caused by such melting disperses the electron beam and the source of x-rays becomes extended. Special precautions must be taken to prevent the anode from melting.

Illustration 3d shows a special type of cathode for microfocal tubes. In an x-ray tube having a pinpoint source such as that shown in Illustration 3e, the beam of electrons emitted by the filament is focused on the anode in a very small area (less than 0.1 mm). To prevent the anode from melting at the point where electrons strike it, the cone-shaped anode is made of tungsten, which melts at 3,500° C (6,332° F). The anode rotates continuously around its axis so that the area struck by the electrons changes continually and has time to cool. The anode is most commonly rotated by an electric motor inside the tube. The tube shown in Illustration 3e has a rotating anode. The electronic apparatus for focusing the electrons as they converge on the anode can be seen mounted on the end of the cathode in Illustration 3e.

3a



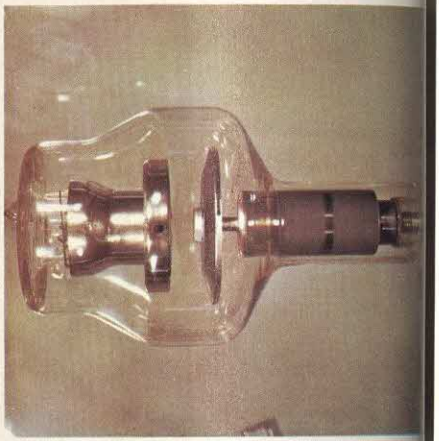
3b



3c

3d

3e



Although x-rays are commonly thought of in connection with hospitals and doctors' and dentists' offices, their most common source is found in almost every American home. It is the television picture tube.

By means of a voltage of about 25,000 volts, a television picture tube accelerates a small beam of electrons onto a fluorescent screen to create a picture. When the electrons strike the screen, they are stopped abruptly, and the energy they release, called braking radiation, is in the form of x-rays. These rays are of low intensity, with wavelengths of more than 1 Å (1 Å equals 10^{-8} cm, or 0.000000001 cm), and most are effectively absorbed by the thick glass of the tube. Because of their low intensity and because only a small number of electrons strike the screen at a given moment, the x-rays from a television tube are not commonly dangerous; nevertheless, it is considered unwise to remain closely in front of such a tube for long periods of time, and defective color television sets with misaligned shields have been known to leak x-rays at 100,000 times the rate considered safe.

The most important and widely used source of radiation, however, is not the television tube but the x-ray tube, which consists of a large diode (vacuum tube) and specially fashioned electrodes. The widespread use of x-rays in radiography and crystallography has created an industry that produces two or three fairly simple, standardized types of x-ray tube. Tubes for both applications are similar in construction.

Two other sources of x-rays are betatrons and synchrotrons, both of which accelerate electrons to high speeds and project them onto a solid target, causing emission of strong x-rays. (When the energy of the electrons is very high, the wavelength of the radiations is extremely short—as little as 0.001 Å. In this case, the radiation is in the form of gamma rays rather than x-rays.)

Certain radioactive substances also can be used as sources of monochromatic x-radiation. In the radioactive process of beta decay, a negatively charged particle is emitted from the nucleus of the atom and the atomic number of the element increases by one unit. The nucleus tends to attract another electron; in the process, x-rays are emitted.

In addition to controlled generation of x-rays, the rays are being generated in the far reaches of cosmic interstellar space. Discrete cosmic x-rays were first detected in 1962 with detectors carried aboard rockets of the U.S. Naval Research Laboratory. By the late 1960s, at least 30 discrete cosmic x-ray sources were detected. Most recently, quasars have been found to be x-ray sources.

THE X-RAY TUBE—Illustration 4a shows the structure of an x-ray tube with its protective casing. This casing protects the tube from electric discharges caused by the input currents and screens the user from the radiations produced by the tube. The glass casing **B** contains the electrodes that emit and receive electrons to produce x-rays. These electrodes are the filament or cathode **F,** and the anode A. The conductors to the cathode and anode pass through the glass casing.

The filament **F,** which emits thermoelectrons, consists of a piece of tungsten wire wound in a coil, much like the filament of an ordinary electric light bulb. The filament is contained in a cavity that is focused on the anode through a perforated diaphragm.

Electrons emitted by the filament are collected in a small area of the anode. The x-rays are emitted from this target area. The anode is of strong metal and extends beyond the glass tube. Because the point at which the electrons are collected becomes very hot, heat from this point is externally dissipated. Cooling takes place through the mounting **M.**

Point **P** of the anode, which is bombarded by the electrons, is constructed of metals that differ according to the kind of x-rays required. When continuous-spectrum radiation is needed, tungsten is used for the target. When monochromatic radiation is required, metals having a lower atomic number than tungsten are used. The anode is set at an angle to the axis of the tube so that the radiations can emerge laterally, through the side of the mounting.

The cooling circuit **R,** which consists of a tube with a high-emission potential and high acceleration, circulates water through the anode. This is necessary because if the heat generated by a power of several kilowatts were not dissipated, the target would melt. Even when cooled, the target is eventually damaged by the bombardment of electrons. When a cooling circuit is fitted, the tube must be wired in such a way that the anode is grounded; otherwise, all the water used for cooling would have to be insulated. In practice, tap water is used. The water-cooling tube is immersed in oil, keeping the temperature of the glass tube uniform and insulating the tube electrically. A difference of potential of 50,000 to 300,000 v exists between the cathode lead and the walls of the glass casing, depending on the purpose of the tube, and the oil eliminates potentially damaging electrical discharges.

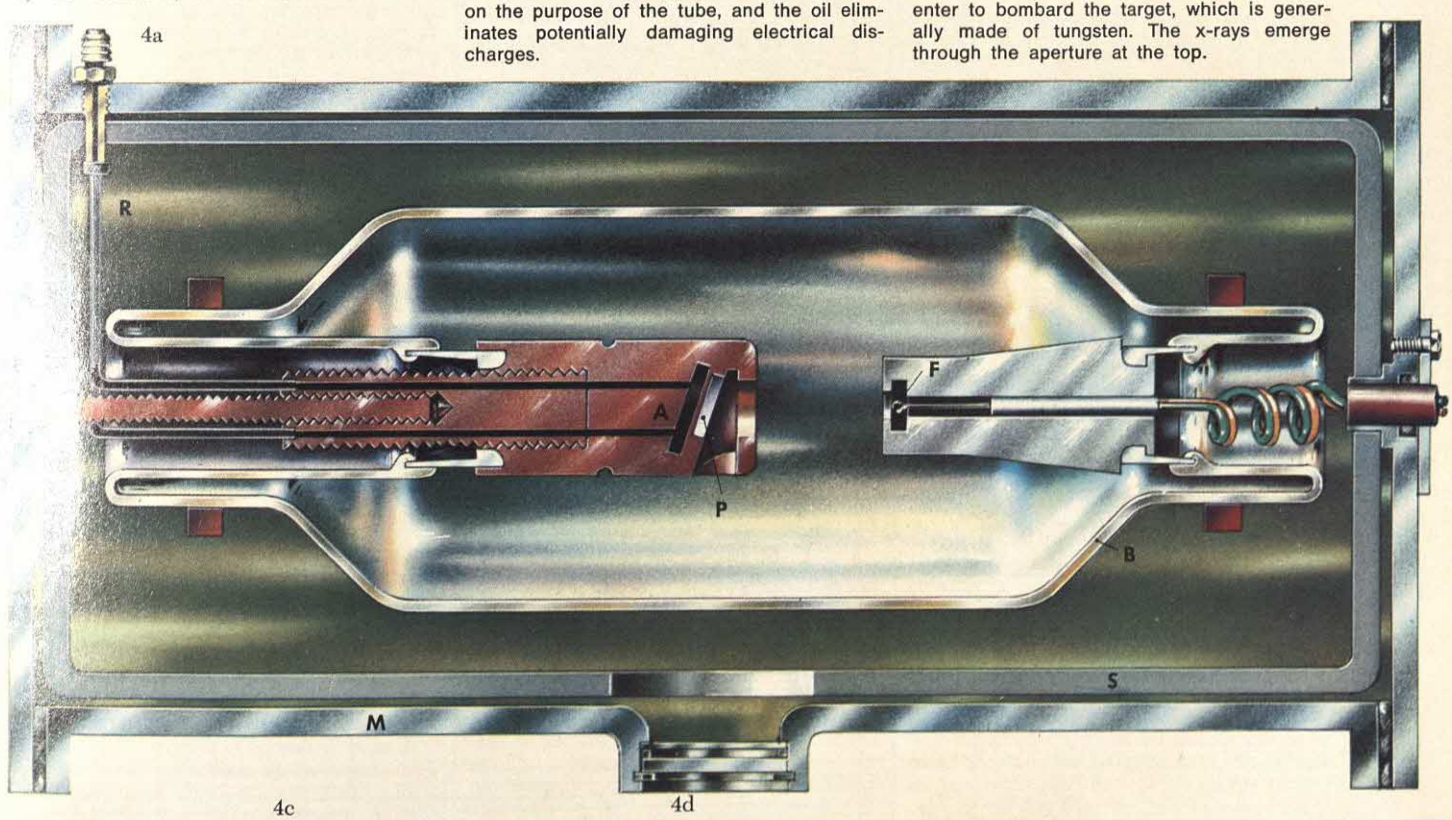
The metal casing **M,** which seals off the tube and oil, provides access for the input lead of the cathode, the power input lead for the acceleration voltage, and the water-cooling tube of the anode. The casing has an opening on one side through which the x-rays emitted can pass. A lead screen **S** prevents the x-rays from dispersing in all directions.

Illustration 4b shows the cathode of an x-ray tube. The tungsten filament that emits the thermionic electrons is clearly visible through the aperture in the front. Two metal plates are placed in front of the filament to limit the space through which the electrons can pass.

The cathode filament shown in Illustration 4c consists of a thick coil of tungsten. The properties that make tungsten so suitable for cathode filaments are a high melting point and a capacity to emit a large number of electrons per square centimeter of surface area.

The anode of an x-ray tube (Illustration 4d) is made of a thick block of copper. Copper is used because it is an excellent thermal conductor and helps to dissipate the heat produced by the electron bombardment. At the left is the aperture through which electrons enter to bombard the target, which is generally made of tungsten. The x-rays emerge through the aperture at the top.

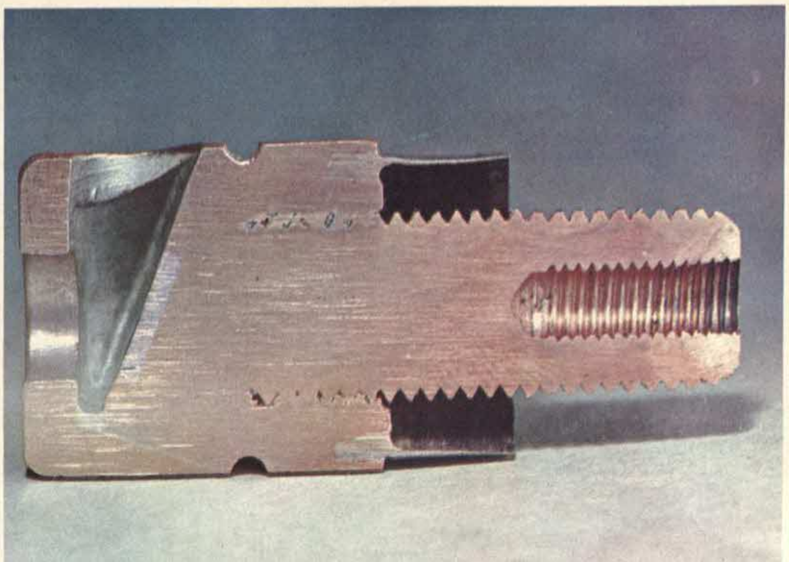
4a



4b

4c

4d



THE ABSORPTION OF X-RAYS

interaction with matter

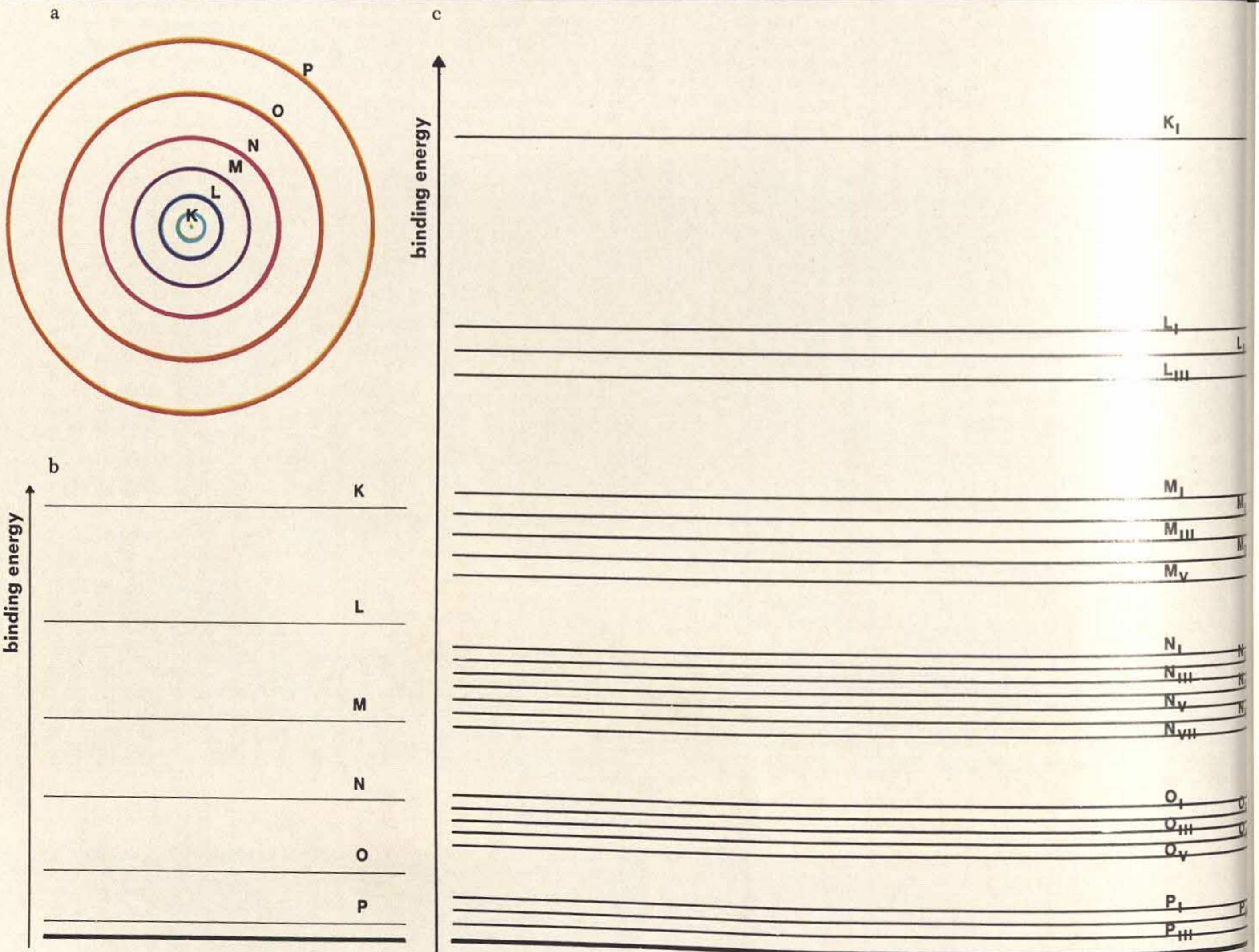
No man has seen an electron—or even an atom, of which an electron is but an infinitesimally small part. Yet scientists have created models of an atom and probed its mysteries with rays that are likewise invisible to their eyes.

To study the bonds between particles that make up atomic nuclei—the protons and neutrons—scientists bombard atoms with particles or rays having an energy comparable to that which binds the protons and neutrons inside the nucleus. This energy is on the order of 8 Mev (8 million electron volts).

To determine the structure of an atom it is enough to bombard it with much less energy than the energy of nuclear bonds. From a few electron volts to slightly more than 100,000 ev is sufficient.

X-rays—invisible rays that possess energy values between thousands and hundreds of thousands of ev—are an effective means of studying both atomic structures and the structure of solids. X-rays can, in

1



THE ENERGY OF THE ELECTRONS IN ATOMS —According to the uncertainty principle developed by the German physicist Werner Heisenberg, it is impossible to determine simultaneously both the exact position of an electron inside an atom and the velocity of the electron. It is known, however, that the distribution of the electrons inside an atom is very complex and that each of them has a particular binding energy equal to the energy that must be expended to expel it permanently from the nucleus.

An intuitive, but by no means strictly accurate, method of representing the electrons of an atom is to assume that they move around fact, expel the electrons from the atoms, thereby causing the emission of characteristic radiations. The energy of these radiations can then be used to discover the structure of the atom.

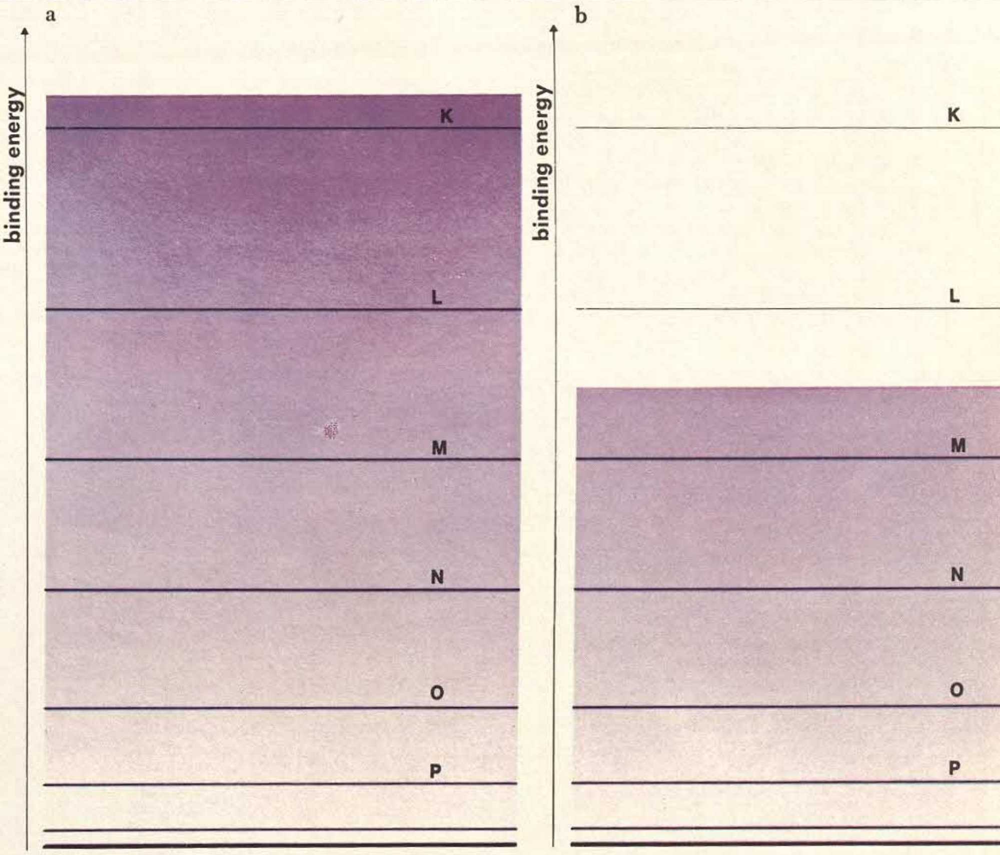
The accompanying illustrations explain the way in which matter can absorb x-rays.

the nucleus in circular orbits (Illustration 1a). Electrons with the same binding energy are shown in the same orbit and at the same distance from the nucleus; those with different binding energies are shown in different orbits. The orbits are designated by capital letters of the alphabet; the innermost orbit is K and the successive ones L, M, N, O, and P. An electron in the K orbit is strongly bound to the nucleus, and high energy is required to detach it. An electron in the L orbit is slightly less strongly bound and slightly less energy is required to expel it from the atom. Moving farther to orbits M, N, and so forth, the amount of energy required to expel an electron continues to diminish.

For greater simplicity, and in order not to be committed to a model that may be intuitive yet inexact, modern physicists generally represent the energy distribution of electrons around a nucleus by a graph showing the energy levels at which the electrons occur (Illustration 1b). On the graph, electrons with the same binding energy are shown at the same level. Those at level K have the greatest binding energy, those at L slightly less, and so forth. Arranging the different levels to an exact scale of energy is not necessary here; it is sufficient to represent their relative positions.

An atomic model showing the electrons rotating in circular orbits around a nucleus must be considered inexact because such a model fails to explain certain atomic phenomena that have been observed experimentally—the multiplicity of certain spectroscopic lines, for example. A less intuitive method that gives a better explanation of the experimental data shows the electrons rotating around the nucleus in elliptical orbits. This method supposes that the various electrons on the same level rotate in elliptical orbits with geometrical characteristics slightly different from one another, reflecting energy differences that are slight in comparison with those between one level and the next. Illustration 1c shows the subdivisions of the energy levels of the electrons arranged in sublevels according to the characteristics of the trajectory of their paths around the nucleus. In an atom with many electrons, the energy sublevels are classified with names derived from the mechanical characteristics of elliptical orbits. In studying x-rays it is sufficient to use a simpler nomenclature—the Bohr and Coster nomenclature—shown at right.

2

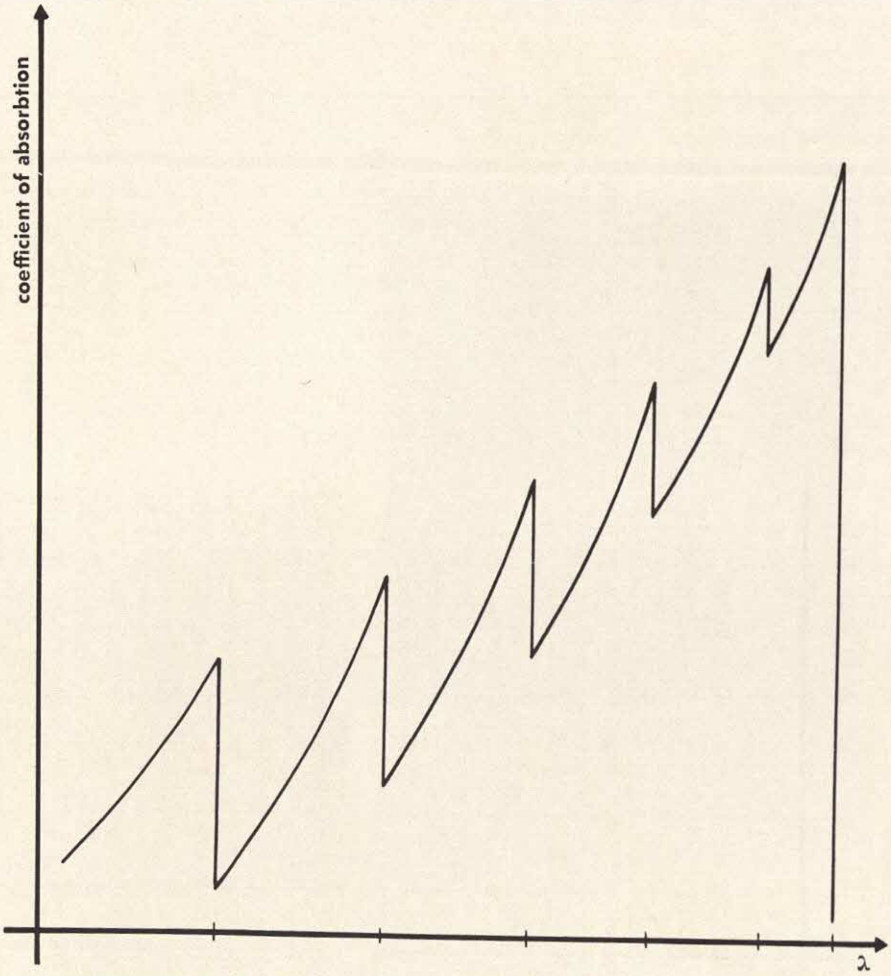


THE ABSORPTION OF X-RAYS BY ATOMS— X-rays, which can pass through matter and among atoms, consist of electromagnetic waves that can produce a photoelectric effect: the dissociation of matter into electrically charged particles. At the energy levels considered here, the photoelectric effect is the chief cause of the absorption of x-rays, resulting in the ejection of electrons from solid matter by photons —individual corpuscles of radiation. To understand the photoelectric effect, it is important to consider the energy with which electrons are bound to an atom.

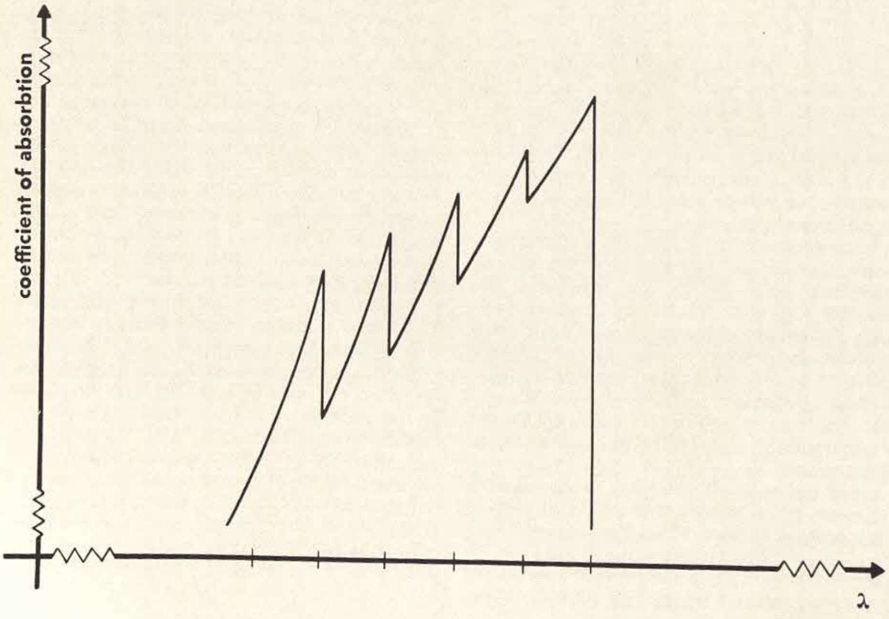
In Illustration 2 the atom is represented by a graph showing the succession of the energy levels and the x-rays by lilac shading of descending intensity, the height of which indicates the energy of the photons. A hard x-ray (one with the shortest wavelength and greatest power of penetration) is represented by lilac shading filling most of the graph; a soft x-ray (with the longest wavelength and least power of penetration) by color in only the lower part of the graph.

When matter interacts with an x-ray possessing much more energy than that with which the electrons at level K are bound to the nucleus (Illustration 2a), the energy of the ray is sufficient to expel any electrons in the atom. In practice, several things may happen. First, the x-rays may pass through the matter without interacting with a single atom, without knocking out any electrons; but if the substance being bombarded is thick, this is most unlikely. Sooner or later an atom will lose an electron. The most likely event is that an electron at the energy level closest to but inferior to the energy possessed by the radiation will be expelled. In this case it would be the electron at level K. Almost all the energy of the x-ray is expended in releasing the electron from its nuclear bond; the residual energy is converted into kinetic energy and used to give velocity to the electron. A less frequent occurrence is that the x-ray may dissipate its energy in releasing an electron not at K, but at L, or M, and so forth. In this case the electron leaves the atom at a greater velocity because less energy is expended in releasing it. The lilac-shaded area covers all the energy levels of the electrons that can be expelled from the atom by the photon—in this particular case, all the electrons of the atom.

In the case of Illustration 2b, the energy of the photon is much less than in Illustration 2a; thus the colored area fills only the lower part of the graph. The electrons at levels K and L cannot be expelled from the atom because the photon does not possess sufficient energy.



3 **THE ABSORPTION POWER OF MATTER**—When x-rays pass through matter, the intensity of the beam is diminished by the phenomenon of absorption. If the material through which the radiation passes is composed entirely of atoms each having a single electron, it is possible to measure the variation of the power of absorption of the material depending on the differences in the energy of the incident radiation. Suppose the material is bombarded with x-rays of variable and increasing wavelengths. The first x-rays will have a very short wavelength, and, therefore, will be hard and able to knock out electrons at any energy level. Because x-rays are absorbed very little, they are known as penetrating rays. If the wavelength is gradually increased, the energy of the photons decreases until it is only slightly above that of level K; the power of absorption is correspondingly increased (Illustration 3). This power of absorption continues to increase as the energy of the photon decreases toward the K level. If the energy of the photon decreases enough, it no longer contains sufficient energy to knock out the electron K and the coefficient of absorption drops abruptly. In fact, the photon is now able to extract electrons only at levels L, M, and so forth. Its energy level, however, remains much higher than that of these levels, so the photon will be unlikely to cause the photoelectric effect and will be easily transmitted—not absorbed. This abrupt variation of the power of absorption corresponding to the energy levels is known as discontinuity. As the energy of the photon is further decreased, other energy levels are successively approached. At each of these levels the power of absorption shows an abrupt momentary increase or discontinuity. Each of these phenomena of discontinuity is usually described by the name of the level to which it corresponds.



4 **THE STRUCTURE OF DISCONTINUITY PHENOMENA**—More accurate measurement of the absorption power of the material and the phenomena of discontinuity caused by the different energy levels shows that other small discontinuities correspond to the sublevels into which each main level is divided. The structure of the energy levels of the electrons of an ordinary atom around level M is shown in the illustration.

The energy of the electrons rotating around the nucleus on their various orbits varies from one atom to another because the forces with which the single electrons are attracted by the nucleus and repelled by the electrons of other atoms also vary.

RADIOGRAPHY

technical and scientific applications of x-rays

When a buyer holds a sheet of paper in front of a light to examine the watermark, the principle is the same as that used in taking x-ray pictures. The buyer looks for differences in the thickness of the paper, observing the different degrees of transparency revealed by the light rays.

Visible light reveals differences in the thickness of paper, but visible light would be totally inadequate for observing the differences in the thickness of a sheet of metal, for example. Paper is transparent because the wood pulp of which it is made reacts to visible light in the same way as powdered glass, which lets the light through and diffuses it. To observe the interior of a metal requires radiation such as x-rays to penetrate the substance. The technique of examining the interior of solid and opaque substances by x-rays is known as radioscopy –if the rays project a visible image on a fluorescent screen–or radiography, if the image is recorded on a photographic plate.

The intensity and quality of the radiation used for radioscopy or radiography are selected to suit the body under observation. For thick bodies and those composed of elements with a high atomic number, a hard and intense radiation is necessary. Certain precautions must be taken in using such radiation because an observer exposed to it could suffer serious biogenetic injury.

Radiography has important applications in medicine, in the technique of mechanical construction, and in the physical studies of metals and alloys. There are almost endless applications in industry–testing of the internal soundness of castings and forgings, correct fabrication of materials, detecting reasons for the failure of mechanical parts. Modern developments include a major increase in the nondestructive testing in art museums, especially for authenticating paintings and for discovering hidden images.

In flash radiography and cineradiography with intense x-ray beams, instantaneous and motion picture sequences are made of rapidly moving or changing objects. Events are recorded over periods as short as one nanosecond (10^{-9} sec). The method is used in ballistics for studying armor-piercing shells, explosions, and the like.

THE PRINCIPLE OF RADIOGRAPHY — The principle on which radiography is based is clarified in this illustration, in which **R** is the tube used to produce the x-rays. The radiation used for observation emerges from the anode. **S** is the lead shielding material that protects the operator and ensures that the rays emerge only in the desired direction. The opaque body to be studied—a hand in this case—transmits and absorbs the radiation in different degrees, depending on the characteristics and constitution of the body. The radiograph is projected onto either a photographic plate sensitive to x-rays, or a fluorescent screen of a material that transforms the x-rays into visible light. If a part of the body is thicker than another part or absorbs a larger amount of x-rays, the amount of radiation transmitted will be reduced, casting a shadow on the screen: in this case the shadow of the bones of the hand.

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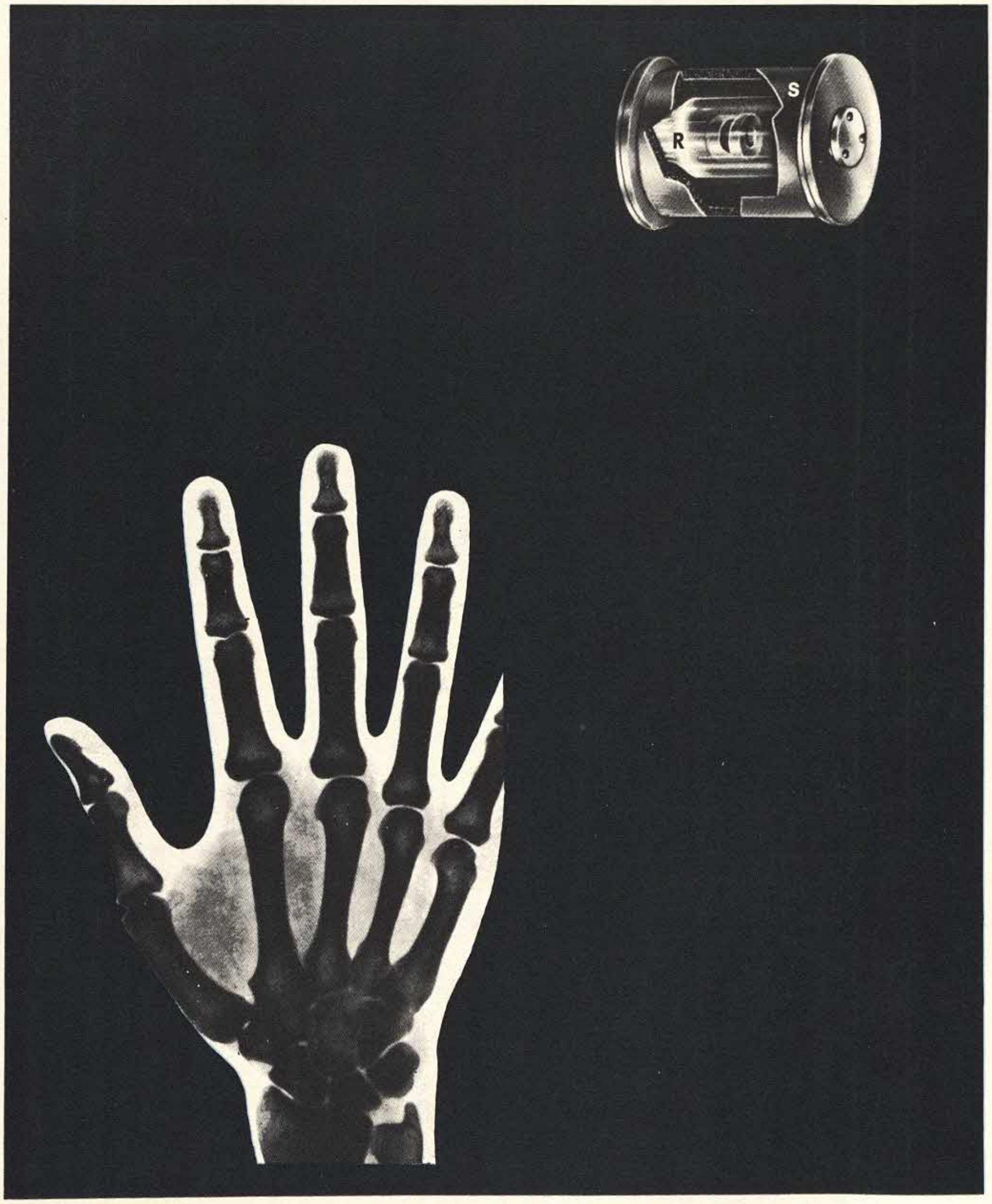


2

THE ABSORPTION OF X-RAYS—Illustration 2 shows the principle on which radiography is based from the physical point of view. A source (at left, not shown) emits monochromatic rays; that is, electromagnetic radiations having a single wavelength—0.3 Å (Ångstrom), for example. The illustrations indicate what happens when these rays strike bodies of different kinds and thicknesses.

In Illustration 2a the radiation emitted by the source at left passes through a thin layer—5 mm (about 0.2 in.) thick—of a substance made up of a single element with a low atomic number, in this case beryllium. The absorption of the x-rays depends on the number of electrons bound to the atoms they meet in passing through. The beryllium atom contains only 4 electrons, and, since it is in the solid state, the atoms are fairly distant from one another—on an average of 2 Å apart. In passing through such a thickness of beryllium, the radiation is only slightly attenuated and is reduced by less than half.

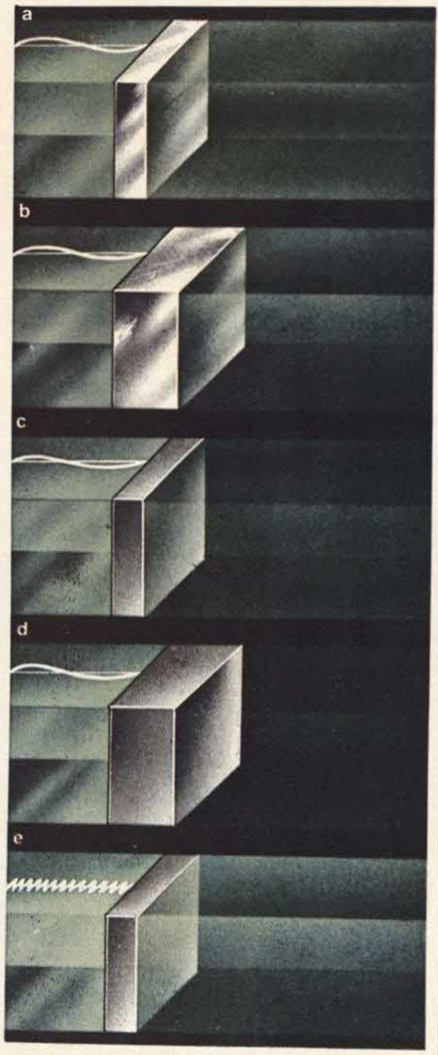
In Illustration 2b the thickness of the beryllium has been increased to 10 mm (about 0.4 in.), and more of the rays are absorbed than before because absorption depends on thickness according to an exponential law.

In Illustration 2c the sample, 5 mm thick, is of an element with a higher atomic number, in this case iron. The atoms in iron are about 2.5 Å apart, but each atom has as many as 26 electrons, with the result that the probability of interaction between x-rays and electrons is increased. Furthermore, the electrons of iron are generally more tightly bound to the nucleus than those of beryllium, a characteristic that also produces an increase in the coefficient of absorption. The 5-mm thickness of iron absorbs the radiation effectively but not completely.

If the thickness of the iron is increased to 10 mm (Illustration 2d), almost none of the radiation passes through the substance.

In Illustration 2e the sample of iron is 5 mm thick, but the x-rays are much harder, having a wavelength of 0.01 Å instead of 0.3 Å. The 5-mm iron sample is opaque to the harder radiation to about the same degree as the 5 mm of beryllium was to a wavelength of 0.3 Å.

The illustrations show that the harder the x-rays used, the greater the penetration, and that not only the atomic number of the elements but the thickness of the object to be examined must be taken into consideration.



THE LAW OF ABSORPTION—When passing through thick objects, x-rays diminish according to the same exponential law that governs the absorption of light. The graph is of x-rays having a wavelength of 0.2 Å, emitted by an x-ray tube fed by a current of 10^5 volts, and passing through a slab of aluminum. Tables have been compiled that give the decrease of intensity as a function of the thickness that has been passed through. This law of diminishing intensity is valid only for monochromatic radiations passing through an object consisting of a single element. For more complex substances and polychromatic rays, as in medical radiography, the law of absorption of the radiation is more complex.

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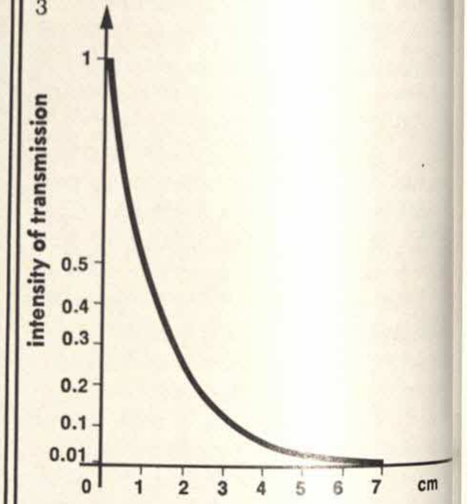

4

DIFFERENCES IN ABSORPTION POWERS—Illustration 4b shows an object made of an alloy of iron and nickel in which the iron is distributed in granules among the nickel. Use can be made of the fact that for radiation having a particular wavelength, iron has an exceptionally high power of absorption. If the x-ray picture were made with polychromatic radiation, it would be difficult to distinguish the iron from the nickel because the two metals have an absorption power that is almost equal. If a particular monochromatic radiation is used, however, the iron will have a high power of absorption and the nickel a low one.

Illustration 4a represents the absorption power of iron for x-rays. The coefficient of absorption is about 50 for x-ray wavelengths longer than 1.743 Å, but rises abruptly to 465 for shorter wavelengths. The radiation on a wavelength shorter than 1.743 Å, for which iron has an extremely high power of absorption, is absorbed only slightly by the nickel. The absorption coefficient of nickel on this wavelength is about 60 g/cm³.

An x-ray picture obtained by using rays with a wavelength of 1.5 to 1.7 Å clearly shows the opaque iron against a background of the transparent nickel (Illustration 4b). This technique (exploiting differences in absorption powers) has its limitations because for the wavelength used the power of absorption is so high that it is possible to x-ray only thin samples of the substance. However, this limitation is not a serious one for a large number of technical and scientific applications.

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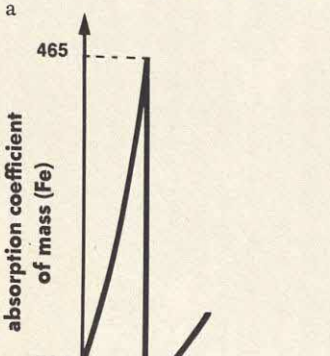

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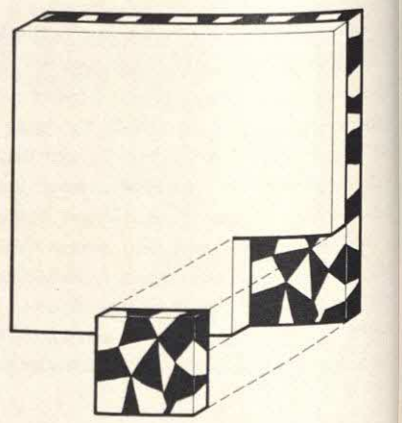

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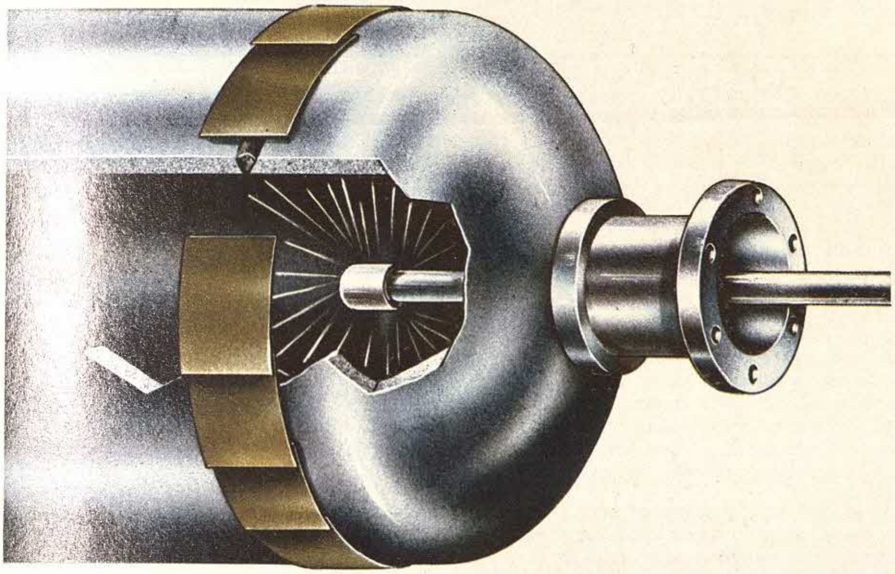

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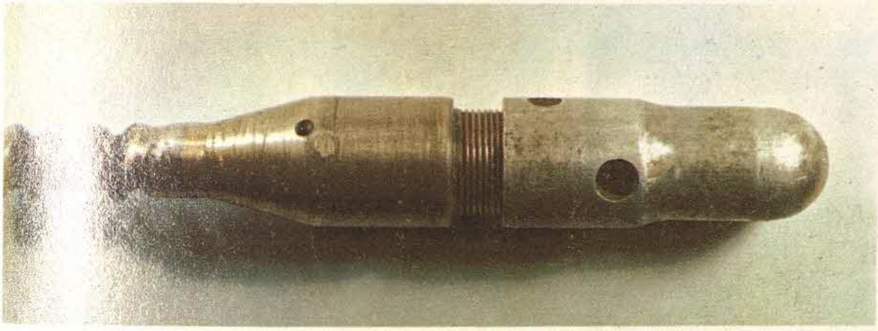


RADIOGRAPHY IN INDUSTRY — Industry makes use of radiography to examine large pieces of metal to see if any cavities were created during fusion, if cracks appeared during the cooling of welded pieces, or if forged or drawn sheets subjected to great strain have developed flaws. The spars of airplane wings and the weldings of large pressure vessels are often x-rayed. Radiography of this sort requires special techniques.

In Illustration 5a an x-ray source has been inserted through the opening of a large vessel made of welded sheet metal. The outer surface of the welds is completely covered with pieces of x-ray film that are numbered in such a way that the area to which each corresponds can be identified. The film is covered with paper to prevent it from being blackened by visible light. The radiation used to x-ray thick sheets of iron must be extremely hard and intense, with a wavelength on the order of a few thousandths of an Ångström. Ordinary x-ray tubes do not produce such penetrating rays and can rarely reach a wavelength of 0.05 Å. The braking radiation produced by electrons emitted by a powerful accelerator is used, but this system works only for special samples. The accelerator is large and could not be inserted into a vessel such as the one shown.

The source most commonly used in industrial radiography is a radioactive isotope cartridge emitting gamma rays (Illustration 5b). These rays are of the same nature as x-rays, except that gamma rays come from changes in the atom or the braking of electrons. By carefully selecting the radioisotope used, radiation of any desired wavelength can be produced. When isotopes are used, the nature of the radiation is measured by the energy of the photon instead of by the wavelength with which it is associated.

6

a

MICRORADIOGRAPHY—By using x-rays it is possible to obtain radiographs with a resolving power superior to that of an optical microscope. The principle on which microradiography is based is the same as that of radiography, but there are certain variations that increase the resolving power.

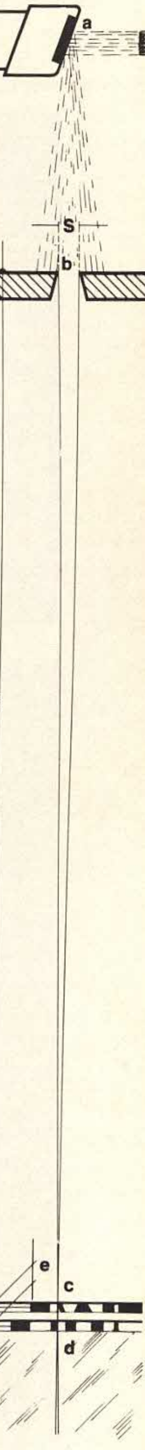
Illustration 6a shows a microradiograph of a ceramic metal, alumina-chrome. The radiograph was obtained by employing an emulsion with a resolving power of more than 2,000 lines per millimeter and shows, in a photographic enlargement of about a hundred times, certain minute details with great clarity.

The black areas, which are caused by a material rich in chrome, would be invisible under an optical microscope; yet they appear here very clearly. The resolving power of this system of observation is limited only by the resolving power of the photographic emulsion.

In Illustration 6b the source is an x-ray tube **a.** Only part of the radiation emitted from the anode is utilized, and the selection is made by a collimator consisting of a lead diaphragm in which there is a small aperture **b.** The substance **c** to be x-rayed consists of a thin strip. If this substance includes a second substance, this second substance will throw a shadow on the photographic film **d.** The clarity of the outline of the shadow depends on these factors: the dimensions of the source (the aperture of the collimator), which has a diameter **S;** the distance **D** between the aperture and sample, and the distance **e** between the sample and film. The width **L** of the penumbra on the film is given by **L = Se/D.**

If **S** = 0.1 mm, **e** = 0.1 mm and **D** = 1 m, the width of the penumbra **L** will be 1/100,000 mm, a much better resolution than can be obtained with even the best optical microscope.

b



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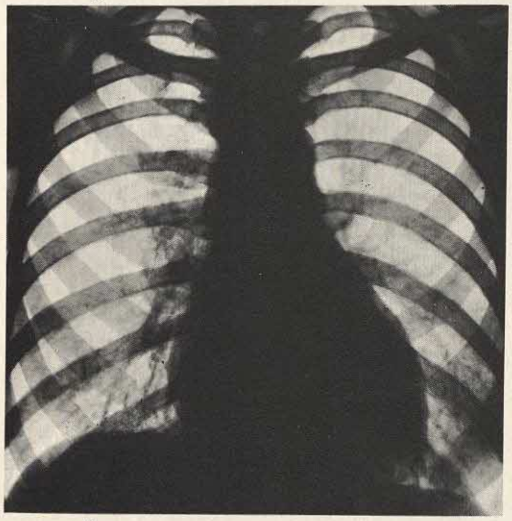


MEDICAL RADIOGRAPHY

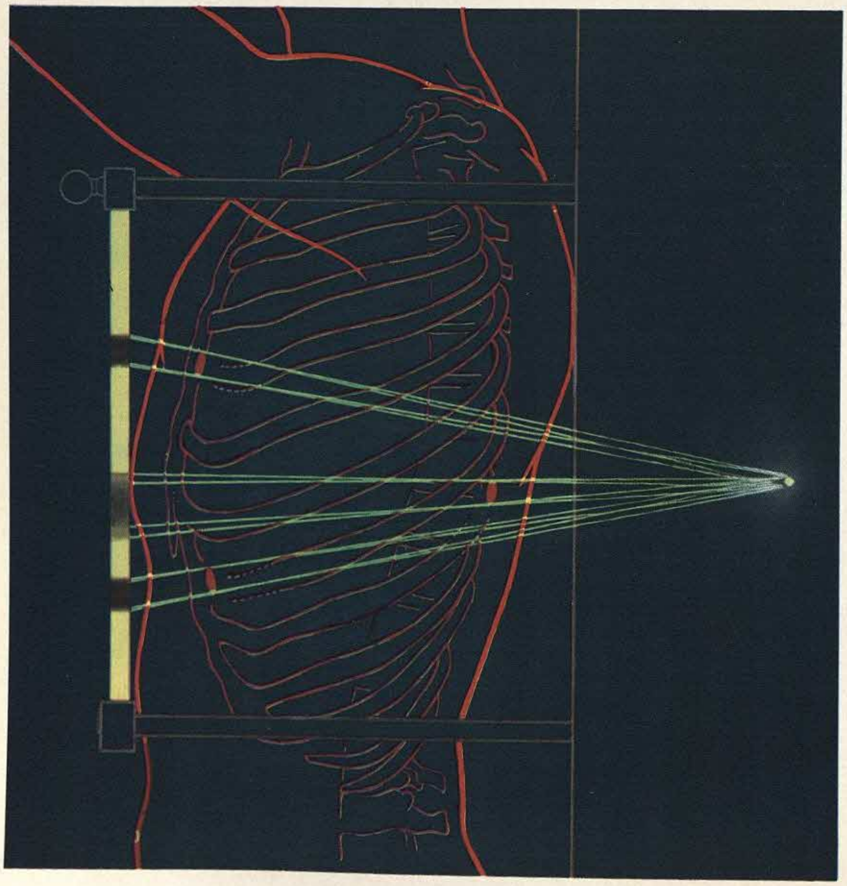
MEDICAL RADIOGRAPHY—The characteristic feature of medical radiography is that it employs radiation from a tube that emits a continuous spectrum of monochromatic rays. An x-ray picture made with this radiation has a penetration power that varies with the different parts of the body. The bones contain calcium and are, therefore, much more opaque to the radiation than the muscles and organs. In an x-ray picture the bones show up clearly. Observation is made directly on the negative (Illustration 7a) because a positive print would blur some of the details.

To distinguish the form, dimensions and position of particular organs requires injecting the organs with a solution containing an element with a high atomic number to provide contrast in the image. Barium is often used for this purpose.

Illustration 7b shows the devices and precautions required in medical radiography. The source of the radiation is that part of the anode struck by the small beam of electrons emitted by the cathode. The source is rather extensive, with the result that the shadow of the body appears blurred—as always happens when a shadow is projected by an extensive light source. The illustration shows how the rays from the source are scattered as they approach the photographic plate. The effect of this scattering is minimized by placing the patient as close as possible to the plane of the photographic plate. Increasing the distance between the patient and the source would cause a considerable loss of intensity of illumination and the exposure time would have to be increased. Care must be taken to keep the patient absolutely still; otherwise, the image will be blurred and useless. In studying medical x-ray pictures, the observer must bear in mind that a radiograph of an object as thick as the human thorax may sometimes distort the perspective of certain details.

Illustration 7c shows an x-ray apparatus. The patient is placed on the flat surface A and must remain motionless if the observation is to be effective. Before taking an x-ray picture, a visual exploration is often carried out. This requires a fluorescent screen that transforms the x-rays into visible rays.

b



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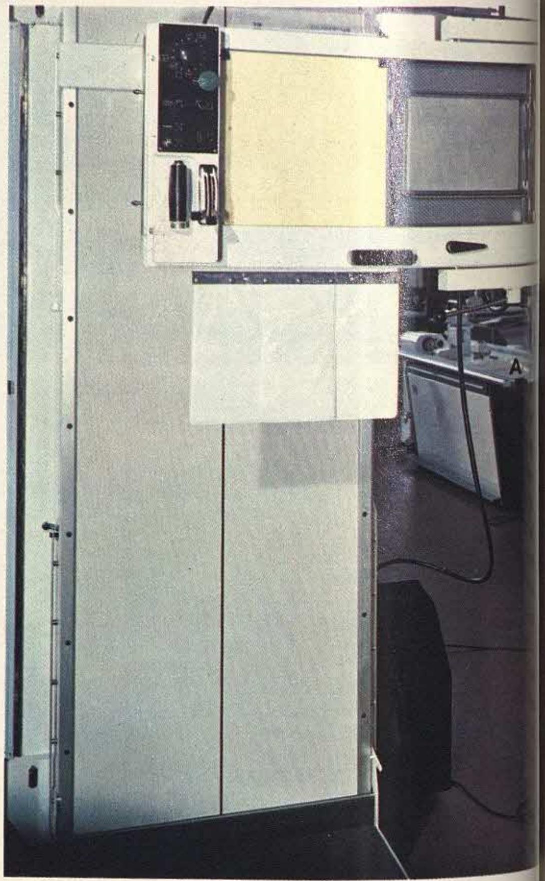


GAMMA RADIATION AND MATTER

the most penetrating electromagnetic waves

When energy is radiated, the radiation may involve quantities of mass or it may involve only a transfer of energy. Radiation of the former kind, corpuscular radiation, is characterized by the emission of a proton, a neutron, an electron, or some other particle. It was discovered, at the beginning of the twentieth century, that the natural radioactivity of certain heavy elements such as radium included the radiation of bodies with positive and negative charges—protons, called alpha rays, and electrons, called beta rays—as well as the radiation of entities without charge and without mass. These were, therefore, designated gamma rays, and were identified as x-rays of especially short wavelength—photons at the end of the spectrum of electromagnetic radiation that includes visible and ultraviolet light.

It was also discovered that, just as atoms subjected to excitation (as by an impact) emit visible or ultraviolet radiation, atomic nuclei subjected to excitation also emit photons—gamma rays. However, it requires much greater energy to excite a nucleus than to excite an atom, and the energy of gamma rays correspondingly exceeds that of light rays. It is usual to define radiation of visible and ultraviolet light in terms of the wavelength of their rays; but at the x-ray end of the spectrum, wavelengths are so short (less than 100 Ångstroms—in the case of gamma rays, less than 0.1Å) that it is more appropriate to describe photons in terms of energy. This is particularly valid because, at this end of the spectrum, the photon has more of the properties of the quantum and less those of the wave than, for example, at the radio (long-wavelength) end of the spectrum.

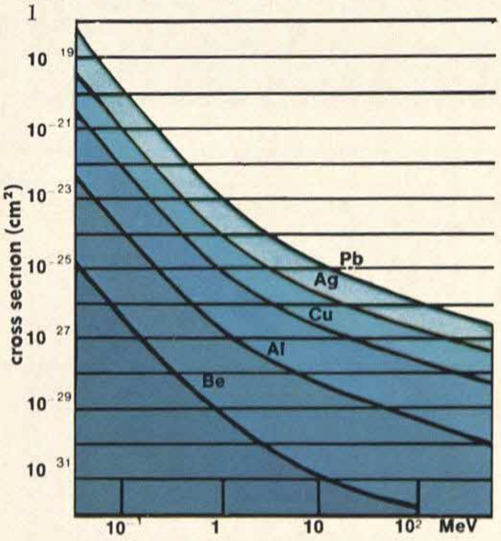
The relationship between the energy and the wavelength of a photon is very simple, and is expressed mathematically as $\lambda = 12{,}340/E$, in which the wavelength λ is given in Ångstroms and the energy E is given in electron volts (ev). The wavelength of a photon of 12,340,000 ev, more commonly written 12.34 Mev, is, therefore, 0.001 Å. This falls within the range of gamma rays (wavelength below 0.1 Å; energy above 123,000 ev or 123 Kev).

One form of gamma radiation is the bremsstrahlung radiations, which are sometimes identified as x-rays, with an energy of some 100 Mev, generated by the deceleration of electrons resulting from impact near the nucleus of an atom.

BEHAVIOR OF GAMMA RAYS

In the case of visible or ultraviolet radiation (and even more in the case of infrared radiation), the photon behaves more like a wave, showing properties of interference, diffraction, dispersion, and refraction. In the case of x-rays and particularly gamma rays, the photon displays properties associated with energy, such as impact and absorption. In its relationship with material bodies, the gamma ray is absorbed at a rate that depends on the density and thickness of the absorbing body, the energy of the photon, and how the photon and the atoms of the body interact. The thicker the layer of the body absorbing (or being penetrated by) gamma rays, the less the intensity of the penetration. This is expressed mathematically, according to a formulation in relation to the absorption of light (sometimes called the Beer-Lambert Law): $I = I_0e^{-\mu x}$; in this formula, the final intensity I equals the product of the initial intensity I_0 and the natural logarithmic base 2.718 (e), raised to a negative power, with its exponent based on the rate of the absorption μ and the thickness of the body x. The value of M depends on the process by which the gamma rays are brought to act on the body. These processes are:

1. The photoelectric effect, in which gamma rays are absorbed and give up their energy to the electrons in the atoms of the body.
2. The Compton effect, in which gamma rays encounter the electrons of the body as though they were all billiard balls, and transfer their energy through mechanical impact.
3. Pair production, where extremely



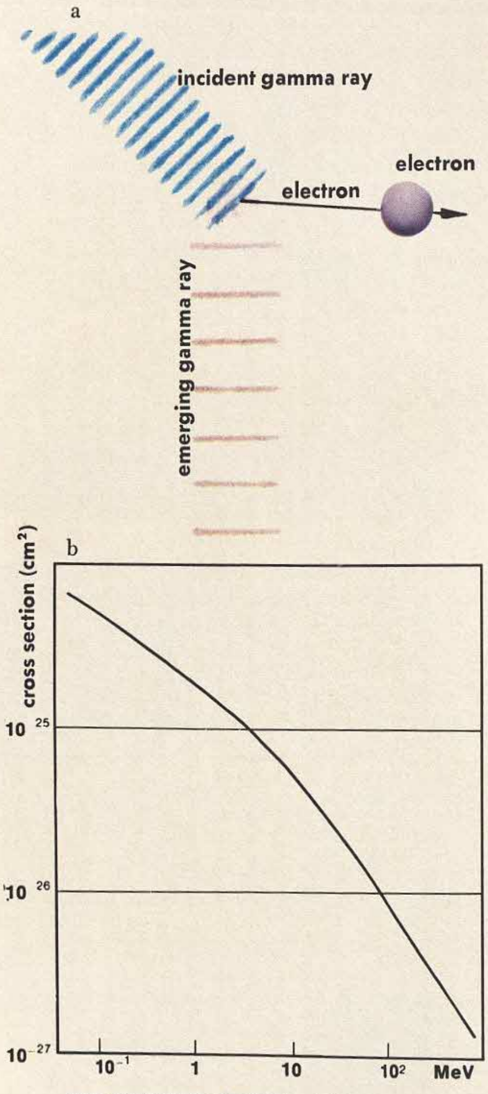
THE PHOTOELECTRIC EFFECT—The principal cause of absorption of x-rays in matter is the photoelectric effect. It is also applicable to high-energy gamma rays. Along the left axis of the illustration the cross section of interaction is given in square centimeters; the greatest probability of absorption of gamma rays by the penetrated matter, following the extraction of electrons from the atoms of that matter, is represented at the top of the axis. The cross section is higher—that is, the probability of absorption is greater—in the case of atoms of heavy elements such as lead and silver, atoms with a greater number of electrons. Moreover, as the initial energy increases (from left to right along the base), the cross section decreases—very rapidly up to approximately 0.5 Mev, then more gradually. If the first part of the diagram, corresponding to low energies (and here the first portion of each curve may be assumed to be slightly wavy), had been drawn in greater detail, it would have shown that the capacity of matter to absorb gamma rays depends on the probability of the gamma rays extracting electrons; and that this probability depends in turn on whether its energy is high enough to extract an electron from an energy level of the atom in question. This illustration shows that the knowledge of the behavior of gamma radiation is satisfactory in regard to energies up to approximately 1,000 Mev; such energies are produced by decelerating particles emitted by accelerators.

energetic gamma rays pass very near an atomic nucleus and are transformed into electrons and positrons, which change part of the energy of the photon into mass.

4. Nuclear photodisintegration, where extremely energetic gamma rays disintegrate a nucleus into its components.
5. Elastic scattering, where atoms, and especially their nuclei, behave as resonators: the gamma rays set the atoms to vibrating, and they then re-emit the energy of the vibration in a direction other than that of the original gamma rays. The emission can also occur in several stages with decreasing levels of emission.

Physicists are interested in studying these phenomena in order to deduce, either theoretically or experimentally, the relationship between the cross section of interaction (the effective area presented to the radiation as a possible target) and the magnitude of μ.

2



THE COMPTON EFFECT—This phenomenon, named after the English physicist Sir Arthur Compton, consists in the recoil of the electron of an atom when the electron is hit by a photon, and is shown in Illustration 2a. A gamma ray hits an electron and behaves as if it had mass and kinetic energy. It jolts the electron with an energy that depends on the angle of the impact; after the impact its wavelength is reduced. Illustration 2b shows how the cross section of this reaction decreases as the energy of the gamma ray increases. The Compton effect can occur at any energy level, but is more probable at an energy level of less than 100 Kev (10^{-1} Mev); when the energy of the gamma ray exceeds 1 Mev, the binding energy of the electron within the atom, almost always less than 100 Kev, is usually negligible.

PAIR PRODUCTION—A gamma ray with an energy exceeding approximately 1.02 Mev has an energy equivalent to the mass of two electrons, when evaluated in mass units according to Einstein's formula, $E = mc^2$. This accounts for the phenomenon of pair production, the creation of matter from energy. When a gamma ray passes near an atomic nucleus, it may be transformed into an electron and a positron (positive electron), and its energy becomes partly the mass and partly the kinetic energy of these particles. Pair production, unlike the photoelectric and Compton effects, becomes more probable as the energy of the gamma ray increases; in excess of a certain limit, however, the probability ceases to increase and a state of saturation is reached.

Illustration 3a shows a gamma ray passing near the nucleus of an atom and being transformed into an electron and a positron; the mass and kinetic energy of these two particles contain the total energy of the gamma ray; for this reason the photon is said to be materialized.

Illustration 3b shows that the probability of pair production depends on both the energy of the gamma ray and on the kinds of atomic nuclei that are approached by the ray. As the energy of the gamma ray advances from the threshold energy of 1.02 Mev to 1,000 Mev, the probability increases; thereafter, saturation occurs. Also, the greater the mass of the nucleus, the greater the probability of pair production.

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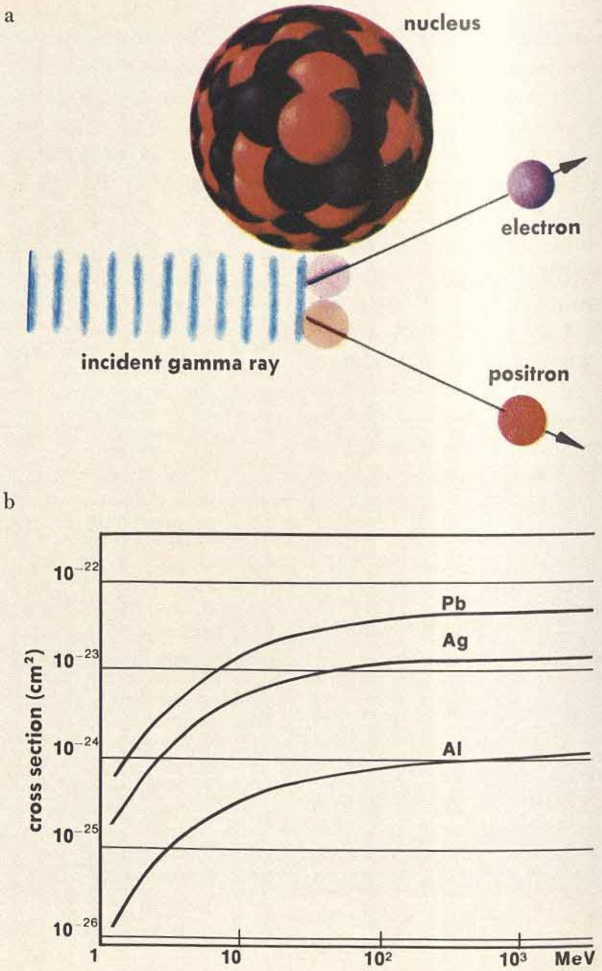

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PHOTODISINTEGRATION—Just as the photoelectric effect results from the extraction of an electron by the absorption of a photon, so the phenomenon of photodisintegration results from the impact of a photon on an atomic nucleus.

A gamma ray striking a nucleus with sufficient energy can expel one of the neutrons (Illustration 4a). Electrons are bound to their atomic nuclei by energies of thousands of electron volts—the innermost shell by as many as 100,000 ev (0.1 Mev); but neutrons are bound within the nucleus by an energy of approximately 8 Mev. It requires very high energy, therefore, to bring about photodisintegration.

Illustration 4b shows the cross section for the photodisintegration of a nucleus; the minimum energy level is seen to be about 8 Mev; the maximum is reached at an energy of two or three times the threshold level, depending on the kind of nucleus, and at higher energy levels this phenomenon is no longer operative; other processes of nuclear disintegration become possible.

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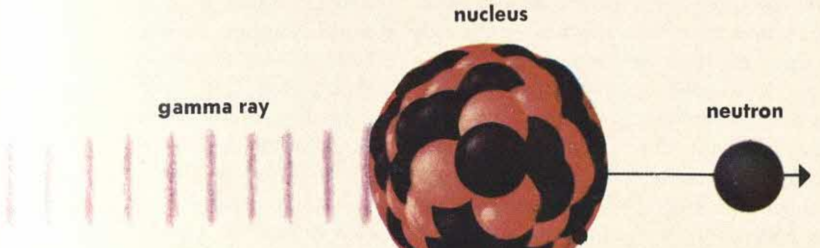

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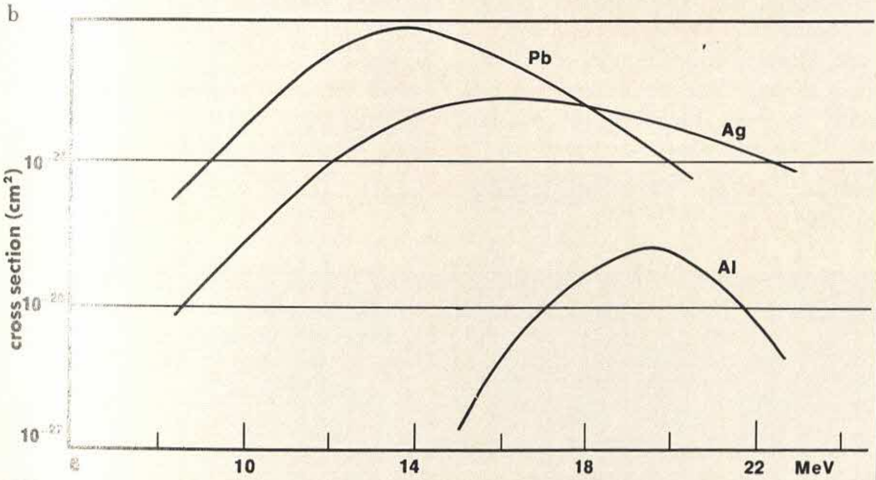

ELASTIC SCATTERING—A gamma ray can strike a nucleus from many angles and become scattered in a direction other than that of its origin, through processes similar to those taking place between less energetic radiations and an atom. These processes are:

1. Thomson scattering, in which the gamma ray strikes the nucleus and sets it vibrating; the nucleus loses energy and emits a gamma ray equivalent in energy to the incident ray, but in another direction.
2. Rayleigh scattering, which occurs through the action of the atom's electrons.
3. Resonance scattering, which occurs when the gamma ray excites an energy level within a nucleus (protons and neutrons are arranged in energy levels similar to those of electrons in an atom), which in turn re-emits the ray.

The general effect of all these phenomena is to cause a change in the direction of the gamma rays; therefore, if the rays are originally collimated, they are scattered without being absorbed. The illustration shows the scattering of gamma rays with an energy just exceeding 1 Mev, striking a block of lead; the gamma ray appears luminous in order to suggest its original direction and subsequent scattering.

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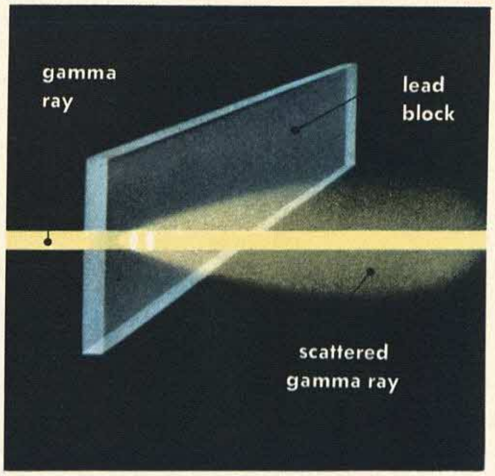

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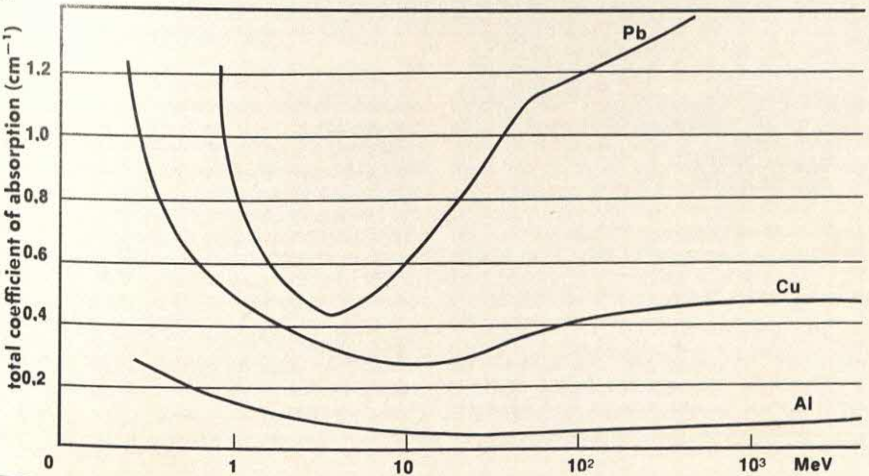


TOTAL ABSORPTION—This illustration shows the absorption curve obtained by combining all the effects that produce absorption of gamma radiation. Three elements are involved: aluminum (Al), with small atomic weight; copper (Cu), with intermediate atomic weight; and lead (Pb), with great atomic weight. Absorption is strong at low energy levels, decreases at about 10 Mev, then increases in the 1,000–5,000 Mev range, with greater increases for the elements with greater atomic weight. A study of these absorption phenomena indicates the complexity of the interaction of gamma rays with matter.

MICROWAVES AND RADIO WAVES

links with the satellites

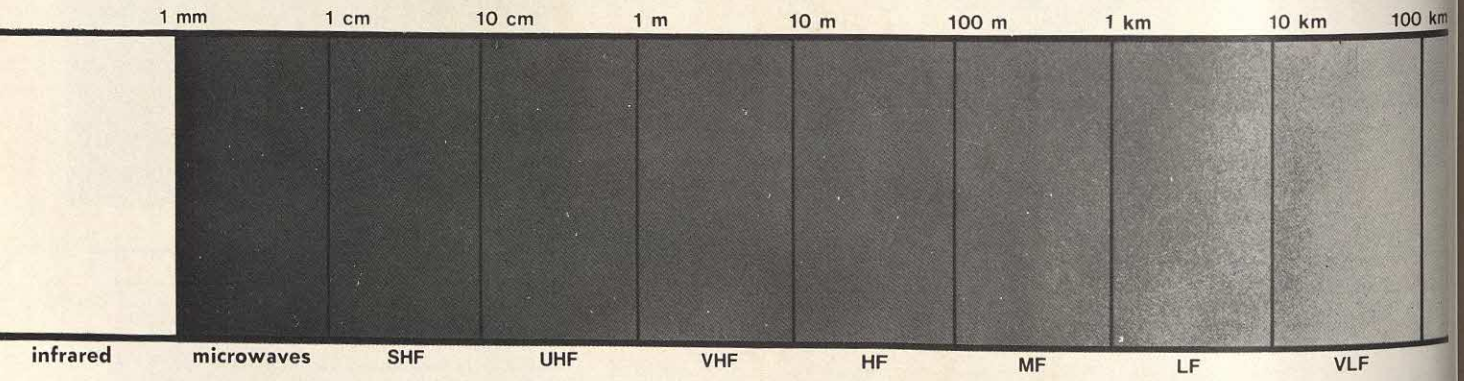
The electromagnetic spectrum comprises radiations of many types, from gamma rays with very short wavelengths to radio waves with very long wavelengths. The latter group—those with long wavelengths, which also include the so-called microwaves—have in common the fact that they are not invariably the result of an energy release in the atomic or molecular level. Gamma radiation involves a release of particles from the nuclei of atoms; x-rays are emitted when electrons change their energy levels within an atom or when electrons collide at great speed against another electron or atom. Ultraviolet and visible radiations result from the passage of electrons from one energy state to another within atoms or molecules; even infrared radiation results from the oscillation of molecules or the vibrations of atoms. All these are radiations of shorter wavelength than microwaves and radio waves, which may result from the passing of alternating electrical currents through conductors, the length of which is comparable to that of the wave of alternating voltage propagated along the conductor.

Microwaves and radio waves also share another important physical property: their electrical fields have a frequency of alternation that is low when compared to those of other electromagnetic radiations. If a solid consists of molecules capable of assuming different orientations under the effect of an electric field, an electromagnetic wave passing through that solid may produce an orientation of the molecules more or less pronounced according to the length of the wave. If the waves are long, the electric field will change direction more slowly than when the waves are short, and the molecules can, as a result, orientate themselves more completely. The dielectric constant and the index of refraction of a solid, in turn, depend on the capacity of its molecules to vary their orientation. Theoretically, at least, the dielectric constant should exactly equal the square of the index of refraction; but this is true with reasonable approximation only when the waves are long; the shorter the waves, the greater the deviation between these two values. In other words, long electromagnetic waves most rigorously satisfy the relationship between the index of refraction and the dielectric constant.

Microwaves and radio waves (the latter are sometimes described as Hertzian waves, in honor of the German physicist Heinrich Rudolf Hertz, who first produced them under laboratory conditions) have numerous practical applications. Both radio and television transmission utilize radio waves. Microwaves, on the other hand, because of their higher frequency (a consequence of their lesser length), are used to study the structure of the molecules of solids, as well as for radar and certain types of radio transmissions.

One branch of physics is concerned with the paths of electromagnetic radiations when they penetrate transparent

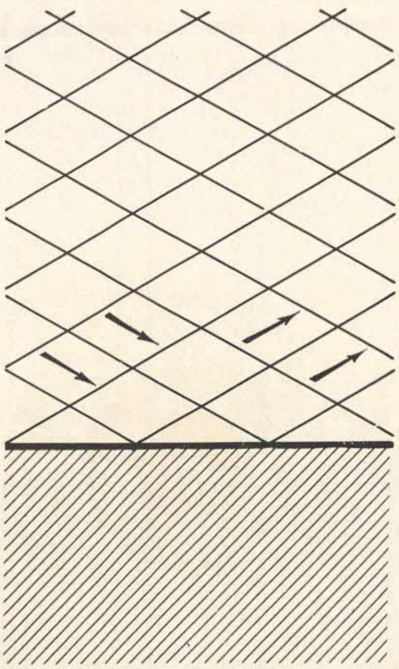
1



THE LONGER WAVES OF THE ELECTROMAGNETIC SPECTRUM—Microwaves and radio waves comprise an important and very extensive part of the electromagnetic spectrum. This illustration shows the various bands into which this part of the spectrum is customarily divided, according to wavelength (at the top) and their corresponding designations (at the bottom). The wavelengths increase in length from left to right, beginning where the infrared radiation leaves off (all radiation with wavelengths of less than 1 mm is generally classified as infrared). The band of microwaves, in its narrower interpretation, comprises radiation with wavelengths between 1 mm and 1 cm, although in some cases the next band, the so-called centimetric band, is also included among the microwaves. This band, with wavelengths from 1 cm to 10 cm, used for telecommunications, is the superhigh frequency (SHF) band. The ultrahigh frequency (UHF) band extends from 10 cm to 1 m; the very high frequency (VHF) band from 1 m to 10 m; and the high frequency (HF) band from 10 m to 100 m. The band between 100 m and 1 km is known as the medium frequency (MF) band; that from 1 km to 10 km as the low frequency (LF) band; and that from 10 km to 100 km as the very low frequency (VLF) band. It must be remembered that the wavelengths increase in inverse proportion to the frequencies.

When the wavelength exceeds 100 km, the field of phenomena associated with slow variations of electric fields has been entered. In this range of wavelengths, electromagnetic radiations do not give rise to any obvious quantum phenomena in their interactions with matter, because the atomic and subatomic particles in matter are bound together with energies that far exceed those possessed by electromagnetic photons. Quantum phenomena, on the other hand, take place whenever there are interactions between microwaves and molecules.

2a



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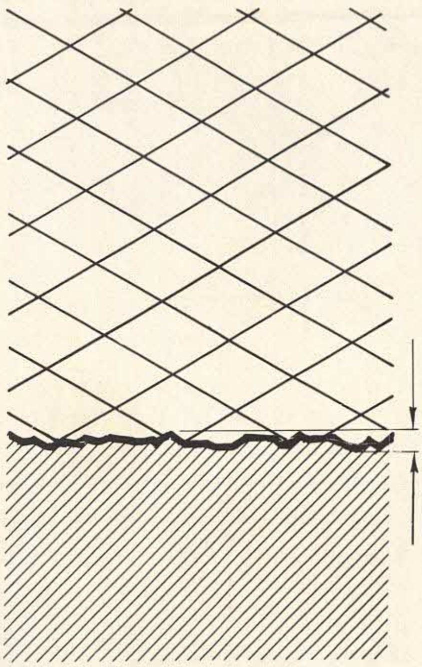

2b

2c

THE REFLECTION OF MICROWAVES AND RADIO WAVES—Before understanding how electromagnetic waves are generated and received, it is necessary to know how they behave—for example, how they are reflected. All electromagnetic waves, whether long or short, behave in much the same way when reflected, and the type of such waves most thoroughly studied, light waves, provides a model. In general, reflection occurs on the surface of a conducting substance such as a metal. Even a gaseous conductor such as the ionized gases of the upper part of the atmosphere—the so-called Kennelly-Heaviside layer or ionosphere—permits the reflection of waves of particular lengths.

The phenomenon of reflection is shown in Illustration 2a. A beam with a well-formed wave front impinges on a flat or curved surface; the trajectory of the beam is deflected according to the laws of optics. However, if the reflecting surface is uneven or rough (as in Illustration 2a′), instead of true reflection, diffusion occurs; and if the surface is very rough, the wave front is destroyed. If the roughness can be gradually diminished, at some point the incident wave ceases to be diffused and is reflected. This point is not precise, but, in analogy with the behavior of light, it may be assumed that it is represented by a degree of roughness at which the up-and-down height does not exceed one fourth of the wavelength of the radiation. If the up-and-down height does not exceed one eighth of this wavelength, the surface is smooth enough to preserve the wave front perfectly.

The machined finish of the metallic surfaces usually used in the construction of reflectors does not seriously affect the reception of SHF or UHF waves. The reflector for microwaves shown in Illustration 2b is made from ordinary sheet metal, and no special care was taken to polish its surface.

Even a perforated sheet or a mesh will obtain a perfect reflection in the case of even longer waves. Such a surface is often used for reflectors of very large size that may be subject to high stresses caused by the wind. Care must be taken, however, that the holes are less than the previously mentioned one fourth or one eighth of the wavelength of the radiation to be reflected. Illustration 2c shows the surface of a reflector constructed in the form of a metal lattice.

Aside from the phenomena of reflection that can be produced artificially in laboratories or in technical applications, it is important to consider the reflections that occur in nature when radiations strike terrestrial or atmospheric obstacles. Among these are reflections by ground surfaces, reflections by the surface of the sea, reflections produced by objects arising from either the land or the sea, and reflection by the clouds of ions and electrons existing in the atmosphere at heights of more than 100 km (about 62 mi).

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bodies or are reflected by opaque bodies—in other words, the optical geometry of their rays. In many respects the optics of microwaves resembles that of visible or ultraviolet radiations. A radar antenna with a parabolic reflector, for example, is substantially analogous to a beacon. This fact has facilitated the solution of various problems encountered in connection with practical applications of microwaves to communications. Large-scale development of microwave techniques for radar use during World War II provided a stimulus in the postwar development of microwave communications systems. A microwave radio-relay system was put into use across the United States in 1951, with six channels in each direction.

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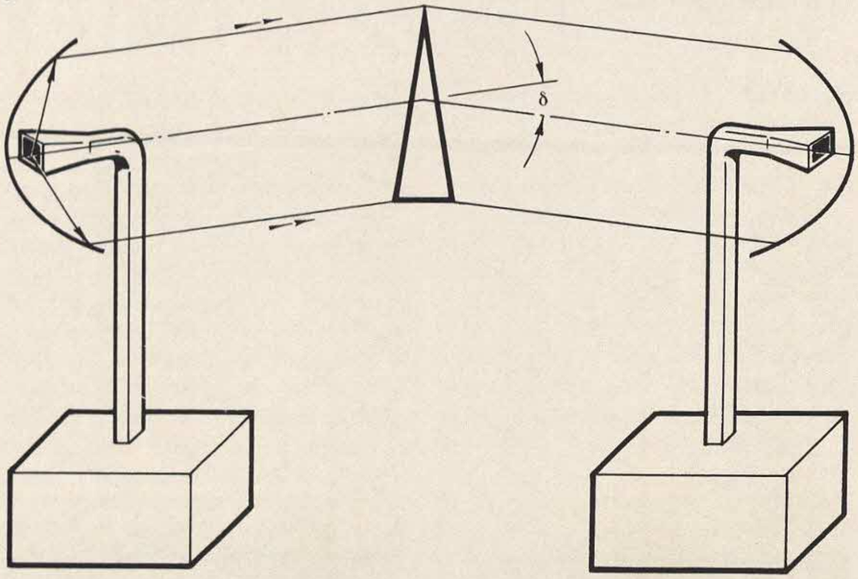
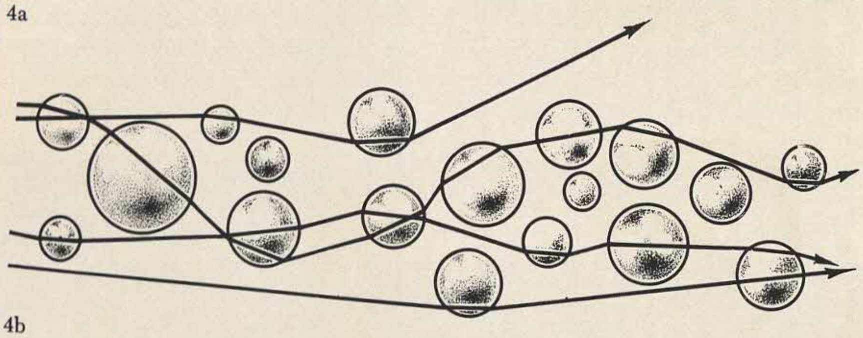


REFRACTION PHENOMENA—Microwaves are naturally refracted when they cross zones of the atmosphere with weak conducting properties, that is, zones incapable of completely absorbing the waves. In the laboratory, it is possible to conduct a scientific test of the refraction of microwaves by producing parallel beams of radiation and measuring the change of direction that occurs when they cross refracting bodies, such as a prism of pitch—a substance composed of aromatic hydrocarbons with a well-defined dielectric constant and an index of refraction very close to its theoretical value. A source of microwaves projects the electromagnetic waves against a parabolic reflector, which renders them parallel and directs them to a pitch prism. After the prism has deflected the waves, an optical system that is the inverse of the preceding one, including a collimator that concentrates the waves into a receiver, shows that the optical system has received the waves from the right direction. If the system indicates the absence of waves, it must be rotated through an angle δ in order to detect them.

4

4a



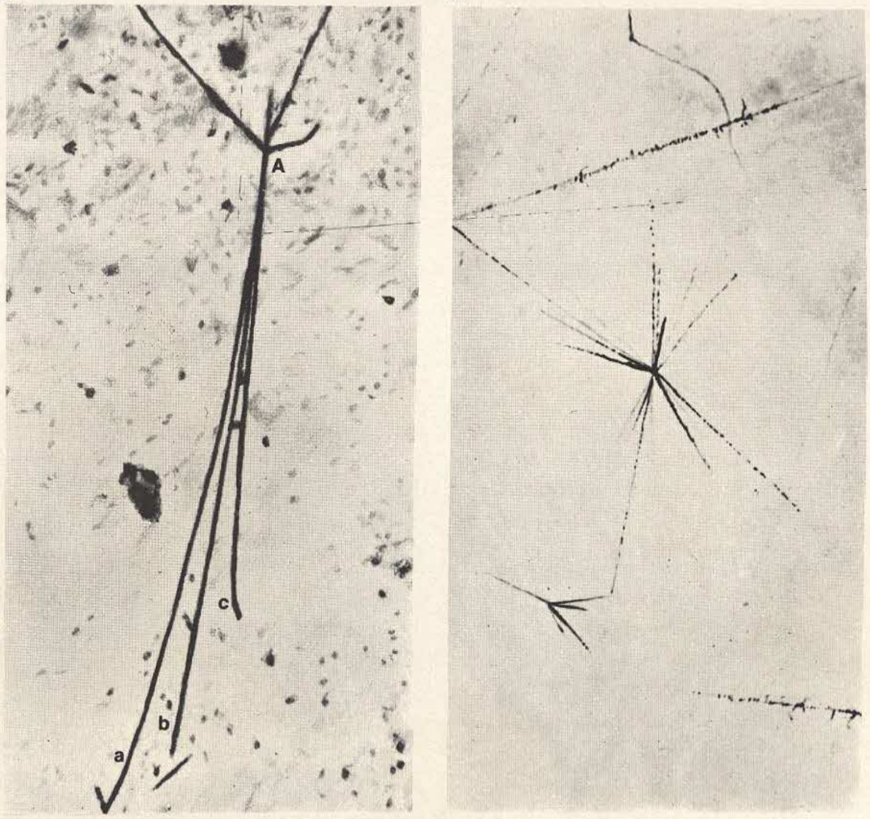
4b

DIFFUSION—This phenomenon is especially important in its technical applications for radio. In order to propagate electromagnetic waves used in radio transmissions, different phenomena can be exploited according to the wavelength of the given radiation. If the radiation has a wavelength in the HF band, for example, the reflection of the upper layers of the atmosphere will ensure that transmission from any point on the Earth's surface will be diffused between the surface and the lower layers of the atmosphere and will, therefore, be capable of reception anywhere on Earth (depending, of course, on the strength of the transmission). Very short waves, on the other hand, can escape from the atmosphere into space and can only be received in the immediate vicinity of the broadcasting station by receivers on a line-of-sight from the antenna of the transmitter. Some transmissions, such as permanent radio links, that are effected by means of parallel beams, even require that the beam be as parallel as possible after projection against the parabolic reflector that acts as collimator. One source of disturbance in such a case is the diffusión caused by the tiny droplets of water suspended in the atmosphere, the matter of which mists and clouds are made. The path of radio waves across such droplets is entirely analogous to the path of a beam of light that becomes diffused; but the refraction index of water for microwaves is much lower than it is for light, and the angles between the sections of the path shown in Illustration 4a have therefore been purposefully exaggerated.

Illustration 4b shows a large dome of plastic material that protects a large radar installation against stresses from wind. The dome is penetrated by the radiations generated within it, and the diffusion undergone by the beam in penetrating the dome does not in any way impair the perfect functioning of the radar equipment.

COSMIC RADIATION | energy from outer space

1



THE RELICS OF NUCLEAR PHYSICS—A great variety of particles and energies cause many nuclear interactions in cosmic radiation. Illustration 1a shows the disintegration of a lithium nucleus **A** with the simultaneous emission of a proton **a**, a deuteron (proton and neutron) **b**, and a tritium particle (proton and two neutrons) **c**.

Illustration 1b shows the disintegration of a heavy nucleus of film emulsion (bromine and silver). Because of the arrangement of trajectories of the disintegration products, this phenomenon is usually called a star disintegration. The nuclear plate reproduced in this photograph was exposed to cosmic rays at a height of about 25 km (about 16 mi).

Interstellar matter is not distributed evenly. The areas where matter is comparatively dense have a nebular (cloudlike) appearance; other areas, where atoms of matter are farther apart, seem to be transparent. A few atoms of gases, such as hydrogen, or of metals, such as iron or calcium, are found among the stars in densities as low as one atom per cubic centimeter. Because one cubic centimeter of the atmosphere surrounding the Earth contains about 10^{19} molecules, interstellar space, by comparison, may be considered empty.

In addition to the atoms already mentioned, a steady bombardment of cosmic radiation (radiation reaching the Earth from outside the solar system), traveling at nearly the speed of light, constantly falls on the Earth from all directions. These rays originate among the extragalactic nebulas, which are separated by distances of millions of light-years.

The term *radiation* refers to a variety of physical phenomena having certain properties in common. All radiations carry energy that penetrates matter and is partly or entirely absorbed by appropriate substances. Radiations are generally divided into two broad groups: corpuscular and electromagnetic. Corpuscular radiations include high-speed electrons emitted in the spontaneous decay of radioactive substances, and artificially accelerated particles, such as cathode rays, which are electrons emitted by the negative electrode, or cathode, during the electrical discharge in a vacuum tube.

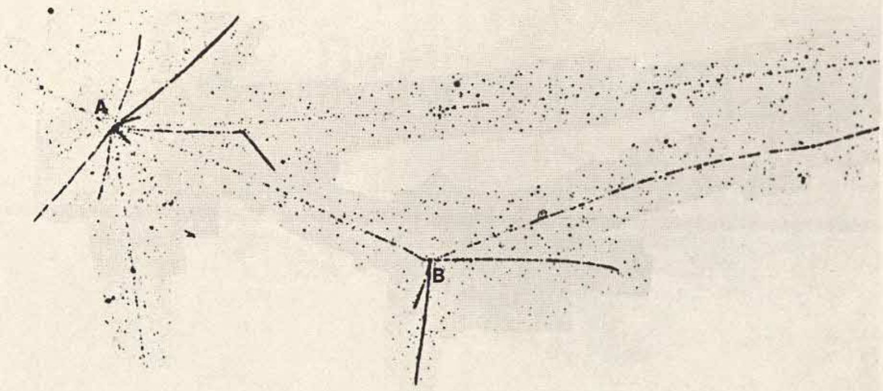
The form of electromagnetic radiation most readily known and studied is light, which originates principally from the stars; the powerful light of the sun is the most obvious example. However, if the sun were a few light-years away, its rays striking the Earth would be as weak as the light received at night from the starry sky.

THE DISCOVERY OF COSMIC RADIATION

For several decades after the discovery of radioactivity, the electroscope was the principal instrument used to study nuclear phenomena. The gold-leaf electroscope consists of a metal case with a glass window; inside the case two thin gold leaves hang from a metal rod (separated from the metal case by an insulating sleeve), which protrudes from the top of the box. The gold leaves are observed through the glass window. Usually the case is electrically grounded.

When a charged substance touches the top of the metal rod, the gold leaves fly apart because both leaves have the same charge and because like charges repel each other. Little by little, however, the leaves drop to their original position as the charge gradually lessens. This is because the air or gas surrounding the leaves of the electroscope is always slightly ionized; that is, it always contains a few free electrons and charged molecules, or ions. If the leaves are positively charged, they attract negative ions, and the positive charge that repels the leaves is gradually neutralized. Negatively charged leaves attract positive ions with the same result.

For a decade scientists had assumed that the discharge of the electroscope, in the absence of any other sources of radioactivity, was due to radioactive elements in the crust of the Earth. Then,



HIGH ENERGY EVENTS—The nucleus at **A** has been struck by a meson that has caused it to disintegrate. The disintegration products include a meson, and this has caused another reaction at **B.**

a few researchers sought more precise reasons for this phenomenon. In 1910, Thomas Wulf of Germany tried to study the natural discharge of the electroscope by carrying an instrument to the top of the Eiffel Tower. From this height he expected the instrument to discharge a little more slowly than it did on the ground because it was farther removed from all sources of radiation. However, the rate of discharge did not change.

During the same year the Austrian physicist, Victor F. Hess, began a series of experiments to measure radiation at even higher altitudes. Taking with him the most sensitive and accurate electroscopes available, he ascended in a balloon to an altitude of 5,100 m (about 16,700 ft), a very great altitude for that time. This was the first of several balloon ascensions by Hess and others for the purpose of measuring radiation. Hess discovered that the electroscope discharged at twice the rate that it had at ground level. From this experiment he concluded that a radiation of very great penetrating power enters the atmosphere from extraterrestrial sources. At 5,000 m(16,404 ft) the instruments were above at least half the mass of the atmosphere, and any radiation originating from the rocks in the crust of the Earth was for all practical purposes eliminated.

Many years passed before Hess's explanation was accepted. The prevailing opinion was that the atmosphere might contain traces of radioactive gases. Other experts thought that the radiation was produced by thunderstorms high in the atmosphere.

From 1923–1926 the American physicist Robert A. Millikan carried out a remarkable series of experiments in cosmic radiation. By 1927 he and most of the rest of the scientific community accepted the hypothesis that the radiation discovered by Hess did come from beyond the Earth's atmosphere. Millikan called this radiation cosmic rays, a name that has been universally accepted.

WHY COSMIC RADIATION IS STUDIED

A knowledge of the variety of cosmic rays and of their properties is essential before a theory of the origin of these particles can be constructed. The studies in the 1920s led to rapid progress in the understanding of cosmic radiation. Since its invention in 1911, the Wilson cloud or expansion chamber has been used to study these rays. This instrument is essentially a glass box with a movable wall, or piston. The box contains a mixture of alcohol vapor and some suitable gas. When the volume of the box is suddenly increased by pulling back the piston, the gases expand and the temperature drops. The alcohol vapor then condenses into droplets, which form a fog in the box. If the expansion is properly controlled, however, a smaller temperature change is produced and the vapor condenses only around ions, which appear as a row of droplets. When these have had time to grow, their track is illuminated with a flash of light, which is photographed. However, the cloud chamber and other devices available during the 1920s were not precise instruments for measuring cosmic radiation, and many erroneous conclusions were drawn.

In 1928 the German physicist Hans Geiger invented a radiation counter, which has become one of the most widely used tools of experimental physics since that time. The Geiger counter, as it is called, is an instrument for detecting and measuring ionizing particles that pass through it. It consists of a closed metal tube with a thin metal wire stretched along its axis. The tube is filled with a suitable gas at a pressure of about a tenth that of the atmosphere. The wire is supported by insulators and is kept at a positive electrical potential so that the tube and the wire can act as electrodes. Knowledge of the precise nature of cosmic rays was greatly expanded by the use of this device.

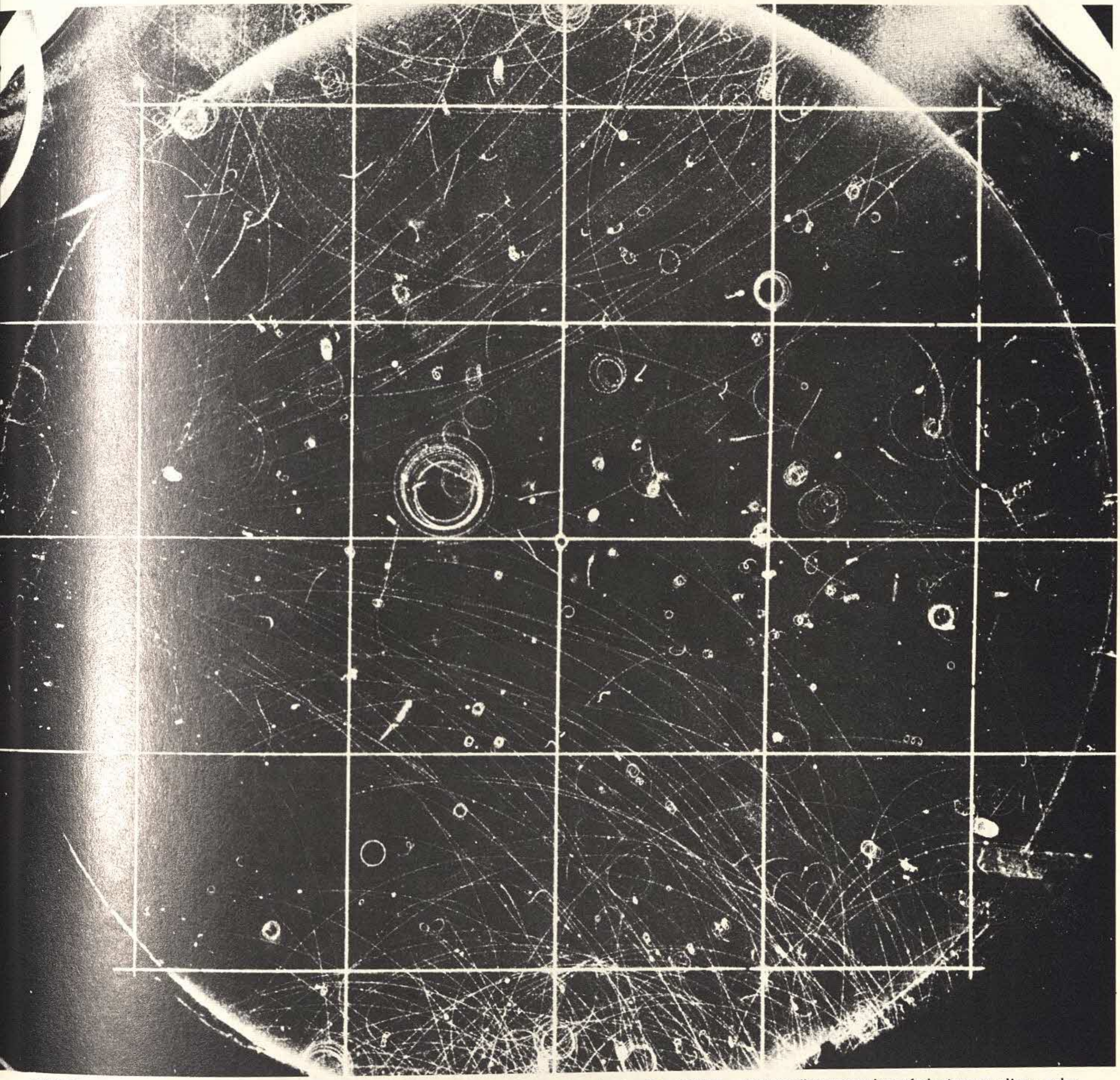
Scientists also continued their studies of radiation at higher altitudes in order to discover possible differences between particles found in interplanetary space and the same kinds of particles that have interacted with the nuclei of atoms in the atmosphere. The Swiss physicist Auguste Piccard made the first balloon flights into the stratosphere in order to study cosmic radiation.

Today cosmic radiation is studied principally through measurements made by space probes and artificial satellites that carry radiation counters and other recording devices clear of the atmosphere and sometimes millions of miles into interplanetary space.

The fields of cosmic ray research are constantly expanding. One of these fields is the study of primary radiation—radiation that has not been altered by passage through the atmosphere. Some scientists are using the Earth as a magnet to analyze cosmic rays. The magnetic field of the Earth extends for a very great distance into space and alters the trajectories (curved paths) of the particles that approach the Earth. Since the magnetic field of the Earth is influenced by solar phenomena, changes in the flow of cosmic radiation can be correlated with solar events.

Experiments are being carried on to study the interactions of very high energy cosmic rays that cannot yet be produced by accelerators in the laboratory. Some particles of cosmic radiation have energies as high as 10^{20} ev (electron volts). The most powerful accelerators are capable of producing particles with energies up to 10^{10} ev, or only one ten-billionth as much energy.

Long-range research programs are being carried on in related areas—programs that may be useful in forming theories regarding the origin of cosmic rays. These include a study of the intensity of radiation with respect to time. The devising of ever more sensitive techniques for radiation detection and measurement has led to extensive study of nuclear transmutations produced by the cosmic rays present in the crust of the Earth. These studies may be useful for showing up geological or biological phe-



LARGE DETECTORS—Technological progress in improving machines and detectors and the development of new devices has made possible cosmic ray research that could not have been undertaken with any hope of success a few years ago. One example is the bubble chamber, which has been changed from a simple device a few inches long to a mammoth, complex detector that covers the walls of the control room. The illustration shows the extraordinary number of electron-positron pairs (diverging trajectories) that can be detected by a modern cloud chamber. The positron was discovered in 1932 in cloud chamber pictures of cosmic rays.

nomena of bygone eras, as well as any variations in the intensity of the radiation that may have occurred through the centuries. Useful indicators may also be found in similar transmutations that cosmic radiation has induced in the elements present in meteorites.

A COSMIC LABORATORY

From studies carried on between 1930 and 1950 physicists had identified the greater part of the elementary cosmic particles—light mesons, heavy mesons, and baryons (particles that correspond to the excited state of the nucleons: protons and neutrons). However, the problems of the origin of cosmic rays and how they acquire their tremendous energies are still unsolved. Discovery in 1968 of the track of a transuranium nucleus in cosmic rays implied a nearby source, perhaps a supernova, because the transuranium elements are short-lived. Of all the forms of cosmic radiation, the nature of light is best understood, and this study is only at its beginnings. The energy brought to Earth by cosmic rays is comparable in quantity to the energy that arrives from all the stars (with the sole exception of the sun). Further knowledge of cosmic rays may produce knowledge of vital importance to the solution of problems in many fields. It may even lead to an understanding of how matter is created in the universe.

BLACKBODY LAWS | characteristics that determine the colors best adapted to everyday use

An understanding of the properties of a blackbody (an object that is a perfect absorber) is important for an understanding of such phenomena as the warmth of the sun and the fact that dark-colored clothes keep people warmer than light-colored clothes. In addition, physicists study and utilize blackbody properties to gain insight into the fundamental properties of matter and of light.

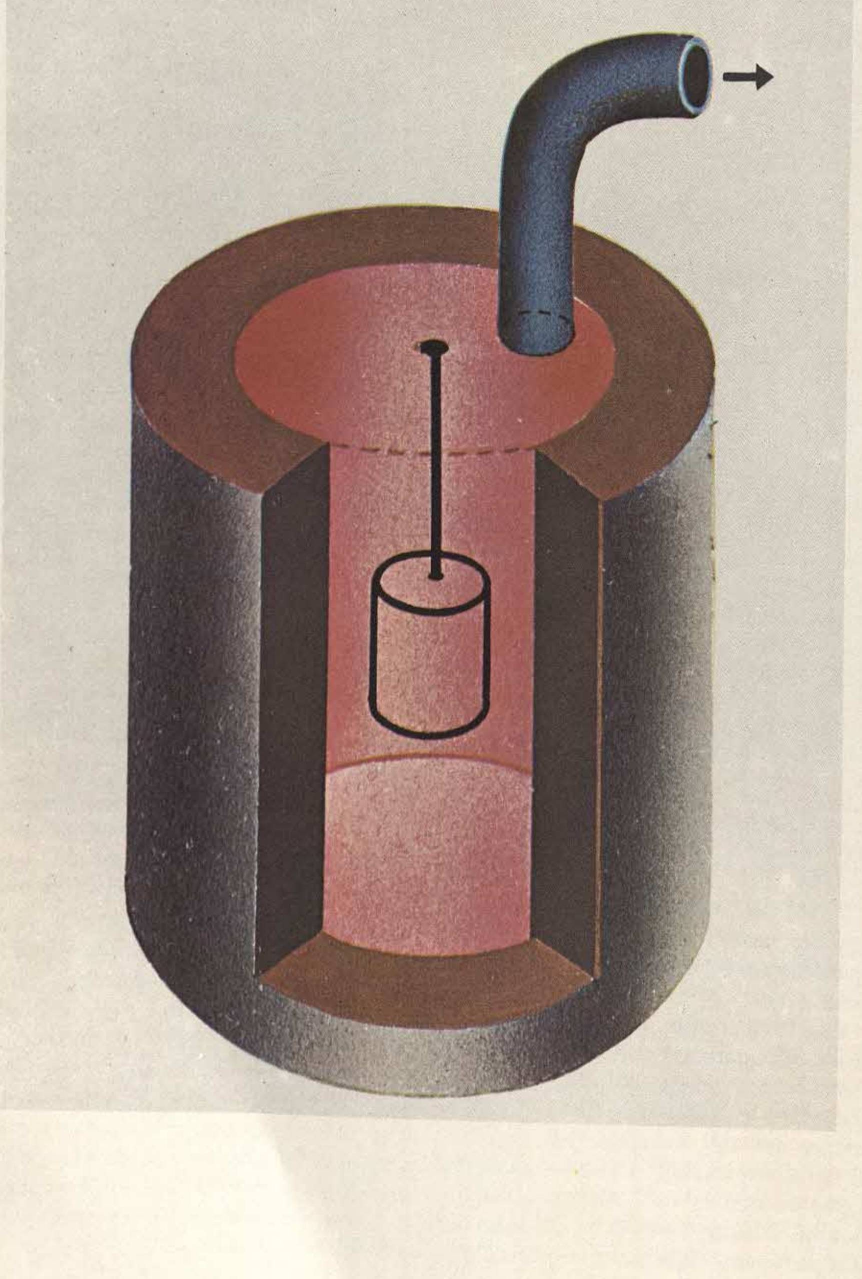
RADIANT ENERGY

Before blackbody properties can be studied, certain other concepts should be understood. Among these is the concept of radiant energy, which can be understood from a mental experiment:

Assume the existence of a container—insulated on the outside with firebricks—from which the air inside is extracted so that a vacuum is created inside the container. The container is heated to a predetermined temperature, perhaps 600° C (1,112° F). Then a lump of any substance that will not disintegrate at this temperature is suspended in the center of the container by a fine metal wire. If the lump is hotter or colder than the container, in a short time its temperature will be equal to that of the container. The heat cannot be transmitted either by the air (since the lump is suspended in a vacuum), or by the wire (for it cannot transmit that much heat so quickly). The heat is transmitted by radiation—energy emitted from the container walls in the same way light is—and absorbed by the substance suspended in the container.

CONDUCTORLESS TRANSMISSION OF ENERGY—A body suspended inside a furnace in which a vacuum has been created cannot be heated by convection. It will be heated, instead, by heat radiated by the walls (Illustration 1a).

1 a



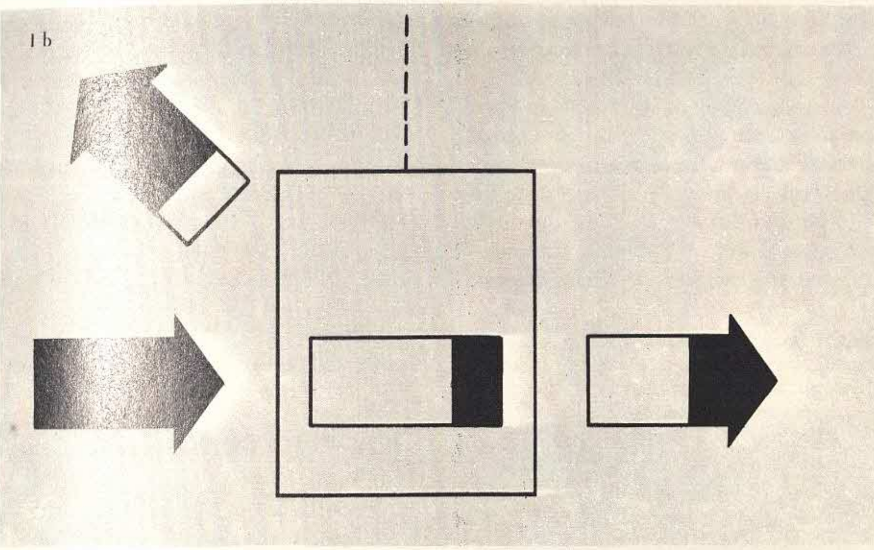
Once the specimen and the container are thermally balanced, however, this exchange of radiant energy does not stop. Energy is still emitted by the walls and strikes the body. This energy is now partly absorbed and partly reflected back toward the walls. What part of the energy is absorbed depends on what is called the absorptive power of the substance, which is measured in percentages. A substance with an absorptive power of 25 percent will absorb 25 percent of the energy that strikes it. Since the specimen and the container are thermally balanced, the specimen must emit as much energy as it absorbs. If the amount of energy that hits the specimen is called *A*, the absorptive power of the specimen called *a*, and the energy emitted by the specimen called *E*, the relationship can be expressed mathematically as

$$aA = E.$$

Since the amount of radiant heat exchange between the walls of a body and its surroundings depends on a, the closer a is to unity, the greater the speed at which energy is exchanged between the specimen and the walls.

THE COLORS OF MANY OBJECTS ARE NOT JUST A MATTER OF FASHION

The phenomena just described involve the absorption, reflection, and radiation



RADIATION—An exchange of heat takes place inside the furnace through radiation, shown by the arrows (above), and continues even after thermal equilibrium is attained.

of thermal energy. However, the descriptions could just as well be applied to light energy. In both cases, the basic unit is an electromagnetic wave, felt as either heat or light, depending on its wavelength.

In the case of visible radiation (light), a very small amount can be detected by the human eye, but the visible rays form an extremely small proportion of the total radiation from any source of artificial light and are absent in radiation from any radiator at a temperature below a red heat. It cannot be assumed that surfaces which appear black to the eye and are practically perfect absorbers of visible light are equally perfect absorbers of the invisible rays. Instruments for detecting or measuring radiation, such as the thermopile or bolometer, depend for their accuracy on the completeness of the absorption of all radiation over a range of wavelength about 100 times greater than that of visible light. The sensitive receiving surfaces of such instruments are necessarily metallic and would be extremely poor absorbers of radiation. They are accordingly coated with a film of lampblack or a similar substance to make the absorption as complete as possible.

Lampblack (smokeblack), consisting of extremely fine particles of carbon, is usually taken as a typical example of a black substance. The majority of black substances owe their blackness to the presence of particles of carbon embedded in a binding medium. (Even black substances reflect some light at the surface when smooth or polished.)

For scientific experiments in which complete absorption of the incident light is required, reflection at the surface must be avoided as far as possible. For this reason, the internal surfaces of optical instruments such as telescopes, microscopes, and cameras are coated with a flat black varnish having a matte surface to eliminate internal reflections that would obscure or fog the image. An absorption equivalent to 98 percent of the incident radiation may thus be obtained under favorable conditions, but it is extremely difficult to estimate the percentage defect and to make sure that it is the same for all wavelengths. Some allowance is usually made for incomplete absorption in modern experiments, but it remains one of the chief sources of uncertainty in accurate measurements.

An example of near-perfect blackness can be seen by removing the lens from a box camera and covering part of the aperture with a card painted with high-quality flat black paint. The uncovered part of the aperture will appear of a much higher order of blackness than the most perfect flat black coating procurable. The advantage of the method lies in the fact that the blackness thus secured is equally perfect for all wavelengths because of the complete elimination of surface reflection at the aperture.

As can be seen from the mathematical law previously expressed, a body that absorbs a great amount of light or heat will reflect only a little light or heat—as *a* approaches 1, the amount that will be reflected decreases. Conversely, a body that absorbs only a small amount of light or heat will reflect a great deal of light or heat.

Experience has shown that the color of an object affects its absorptive power. Dark-colored clothes are warmer than light-colored clothes. This is why summer clothes are often white or pastel, while winter clothes are often dark or black. This fact has been exploited in many ways. In those countries with glaciers, when a glacier is advancing too rapidly, a dark substance (like lampblack) is sprayed over the glacier to help melt it. A vacuum bottle is also a good example of how this phenomenon is utilized. Such a device consists of a double-walled glass bottle placed inside a metal protective casing. A vacuum is induced between the two glass walls so that heat cannot be transmitted to the outside container by convection. To avoid transfer of heat by radiation, the surfaces of the glass bottle are covered with silver. Silver has a low absorptive power, which prevents a rapid transfer of heat outside the bottle.

EXPERIMENTAL CONFIRMATION

The following experiment proves that bodies with high reflective power and low absorptive power cannot emit a significant amount of radiant energy because they do not absorb very much, while bodies with low reflective power and high absorptive power emit significant amounts of energy.

Two small, highly finished copper blocks are coated, one with chrome, the other with black copper. The blocks are then placed in a furnace heated to not more than 700° C (1,292° F). After both blocks reach the temperature of the furnace, it can be seen that the chrome-covered block emits either no light or barely perceptible light, while the black-coated block emits a dull red light (see Illustration 2). Space vehicles are often coated in black and white patterns to control heat radiation inside the spacecraft.

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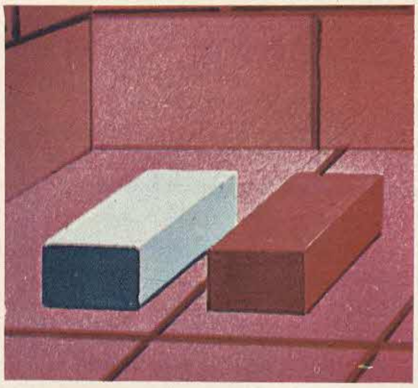

POOR ABSORPTION EQUALS POOR EMISSION—At 700° C (1,292° F), two bodies, one coated with a chrome finish and the other with a black finish, appear, respectively, dark and red. This is visible proof that the body with the lower absorptive power (the body with the chrome finish) is less emissive, while the body with the higher absorptive power (the body with the black finish) is more emissive.

THE BLACKBODY

Some bodies are so absorptive that their absorptive power is close to 100 percent. By virtue of the equation $aA = E$, they also are highly emissive. When cold, they emit radiant energy at a wavelength not visible to the human eye, and appear black. The sun is such a blackbody and would not reflect anything if it were illuminated.

Illustration 3 is a drawing of an almost perfect blackbody called a Kirchhoff cavity. This is a container with a hole bored in its wall. The light entering the hole hits a point inside and is reflected many times before even a small part of it is reflected back out through the hole. Thus, almost all the radiant energy is absorbed. A Kirchhoff cavity, named for Gustav Kirchhoff, the German physicist who first studied the theoretical laws of radiant energy, emits exactly the same radiations that a perfect blackbody would emit at the same temperature, no matter what color its inner surface.

BLACKBODY RADIATION

The study of the radiation emitted by a blackbody has resulted in many important scientific discoveries and useful applications. Aside from these, the results of blackbody radiation study can be generalized for all bodies, regardless of color. A body reacts in the same way as a blackbody to the degree that it is black: the darker a body, the closer its absorptive and radiative properties are to those of a blackbody.

A careful study of the results of the experiment shown in Illustration 4 reveals several important basic properties of blackbody radiation and suggests certain applications for them. First, the higher the temperature at which radiation is emitted, the more predominant the violet end of the spectrum. This property allows temperature to be measured on the basis of color. The optical pyrometer, an instrument used for measurement of furnace and molten metal temperatures at a distance, is an example of the use to which this property has been put. A common type of optical pyrometer looks like a small telescope. Inside is an electric lamp, heated by a current that is controllable. The control is adjusted until the

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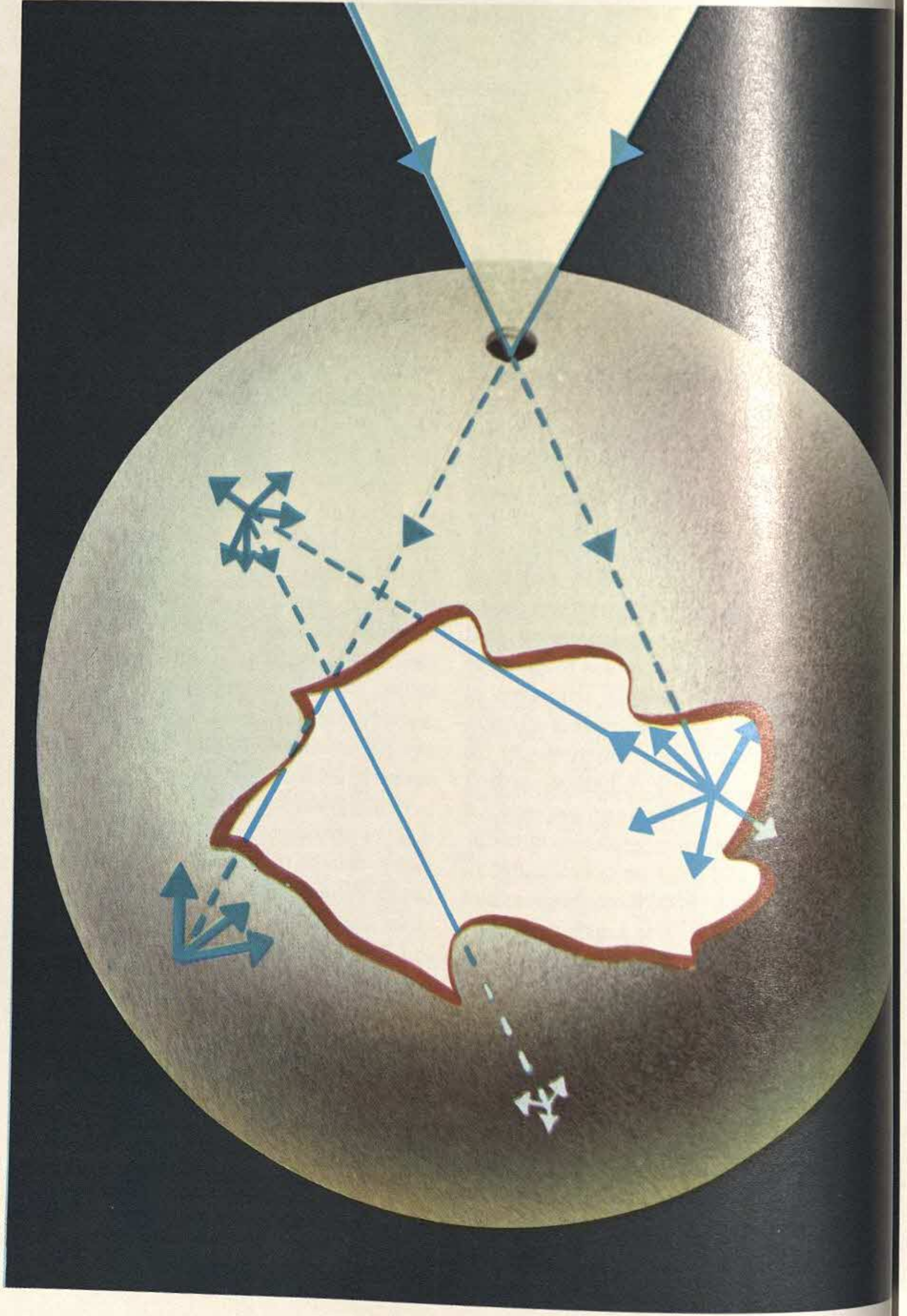
BLACK AND BLACKER—A body with a black exterior is not always a perfect blackbody. However, a hollow container with a very small opening to allow radiation to escape or enter has the characteristics of a perfect blackbody.



lamp matches the radiating surface in brightness. The current required to do this is read from a scale which is marked for temperatures.

Any substance that has been vaporized and subjected to extremely high temperatures also acts like a blackbody. This property is used to equip nuclear warheads with a so-called "eye" to sense radiations invisible to the human eye. Such a sensing device acts as a guide for the missile. An even more striking use, however, is in stellar astronomy. Distant stars also exhibit blackbody characteristics; thus, not only the temperature of a star, but also the events occurring inside it, can be determined from a study of the radiations emanating from the star. Solar radiation, as it reaches the outside of the Earth's atmosphere, is in quality quite similar to that of a blackbody at 5,800° K (about 5,530° C), and is effectively contained within a spectrum extending from about 0.2 μm wavelength in the ultraviolet to about 3 μm in the infrared, maximum energy falling near 0.5 μm in the visible region. The blackbody radiation of a source like the sun is the temperature at which a blackbody would emit radiation of the same intensity.

An analysis of the spectrum of a heated blackbody also reveals that at any temperature, the spectrum of a blackbody contains many different visible and invisible wavelengths, although one color may be predominant to the human eye. For example, at 500° C (932° F), when a blackbody glows dark red, a number of electromagnetic waves of different wavelengths are emitted.

RELATION BETWEEN BLACKBODY RADIATION AND TEMPERATURE

A final property of blackbody radiation is that the total amount of radiation emitted increases at a rate faster than the temperature. Doubling the temperature produces sixteen times the intensity of radiation. An example of this phenomenon can be seen, inversely, every time a powerful lamp is turned off. Immediately, the brightness of the filament decreases—at first very rapidly, and then more and more slowly—until it is finally dark. The law of progression that it follows is not proportionate to the more gradual fall in temperature.

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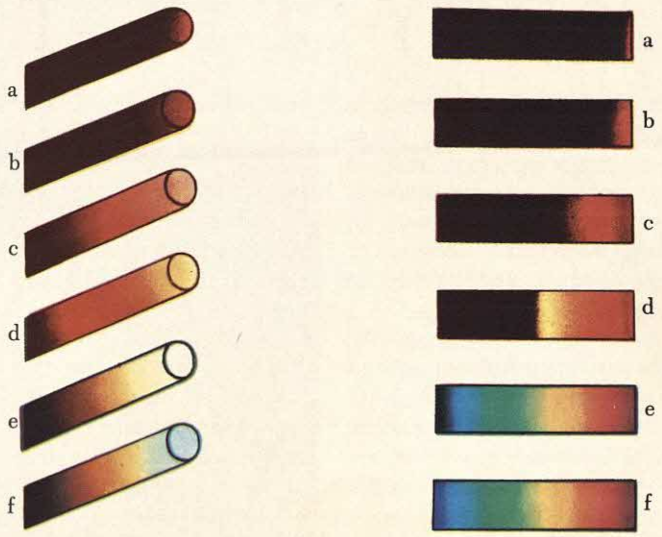


BLACKBODY RADIATION—(a) 550° C (1,022° F). A reddish light is barely noticeable. The visible spectrum contains only a little red on the end.

(b) 600° C (1,112° F). A faint dark red light is emitted. The visible spectrum contains slightly more red than before.

(c) 800° C (1,472° F). The light becomes orange in color. Orange is also present in the visible spectrum.

(d) 1,200° C (2,192° F). The light is a very intense yellow.

(e) 2,000° C (3,632° F). The light is very intense and white. All the colors of the spectrum are present except violet, which is still faint.

(f) 20,000° C (36,032° F). At this temperature a substance is no longer either solid or liquid. However, assume that the experiment continues with a solid blackbody. In this case, the light emitted is intensely blue. All the colors of the spectrum are present, with strong predominance of the violet band.

In 1879, the Austrian physicist Josef Stefan first stated this law of progression: the total radiation of a hot body (blackbody) is proportional to the fourth power of its absolute temperature.

The most complete verification of the fourth-power law was made in 1897. First, a blackbody heated by steam at 100° C (212° F) was used to standardize a bolometer. The radiator was a blackbody consisting of a copper sphere heated in a salt bath for the range 200 to 600° C (392 to 1,112° F), and an iron cylinder heated in a gas muffle for the range 600 to 1,250° C (1,112 to 2,282° F). The temperatures were taken with a high-range mercury thermometer, and with thermocouples, corrected to the gas-scale by direct comparison with a gas thermometer up to 1,150° C (2,102° F). One of the chief experimental difficulties of this investigation is the wide range of variation of the intensity of the radiation to be measured, which is nearly 450 times as great at 1,250° C as at 100° C. The experimenters employed an extremely sensitive type of bolometer, and a galvanometer capable of giving a deflection of 336 mm (about 13.2 in.) under standard conditions, with a beam of radiation 16 mm (about 0.62 in.) square at a distance of 633 mm (about 25 in.) from the blackbody at 100° C. For the higher intensities, it was necessary to reduce the sensitivity in a known ratio by varying the distance of the bolometer from the source, and the current in the bolometer circuit. The results for the relative intensities agreed on the average to about one percent with the fourth-power law over the whole range of the observations. The law has since been verified up to 1,500° C (2,732° F) by extending the range of the gas thermometer and thermocouples, and down to −250° C (−418° F) with bolometers.

The fourth-power law is sometimes called the Stefan-Boltzmann law because the Austrian physicist Ludwig Boltzmann showed, in 1884, that the fourth-power law could be deduced from thermodynamic principles.

TEMPERATURE AND QUANTITY OF HEAT

hot objects do not always contain a great deal of heat

The way in which man keeps warm in a cold climate, the sparkling of a distant star, or the functioning of an internal combustion engine can be explained in terms of temperature and quantity of heat. In fact, the relative "hotness" or "coldness" of a body is used to explain a great many physical phenomena.

One difficulty in understanding the theory of temperature is defining hot and cold. An object may feel hot or cold to the touch, but such definitions are rather inexact. What is needed is a more precise, scientific definition of temperature and its effect on matter.

The sensation of hotness or coldness that is felt when contacting another substance is relative; that is, the object touched can be either hotter or colder than the hand that touches it. The exact degree of heat felt can only be determined by an instrument such as a thermometer. By placing several objects in a row so that each one will always be hotter than the one to its left, it can be said that all of the objects are classified according to their relative temperature. In the same way, mixing two glasses of hot and cold water in a third container creates a liquid with a temperature value somewhere between the two original temperatures. A heat exchange has taken place in which the colder liquid has absorbed heat from the hotter one.

These simple experiments demonstrate the existence of heat and the ability of bodies to exchange this heat. The thermal state of a body is, then, one definition of temperature. From the sense of heat naturally derives the idea of a continuous scale of order expressed by such terms as summer heat, fever heat, and white heat, in which all bodies may be placed with regard to the degree of hotness as distinct from the quantity of heat they contain. It can be observed that boiling water will cause serious burns to a hand in large enough amounts, but a drop of water of the same temperature will not cause a serious burn. The reason is that a single drop will not succeed in heating the surface layer of skin. In this case, the quantity of heat available is the determining factor as well as its temperature.

It can be seen that temperature and quantity of heat are really two different things. This difference can be further demonstrated by heating a needle in a flame and immersing it in water. The resulting hiss and the fact that the needle quickly cools shows that the temperature of the much smaller object has been strongly affected by the large quantity of water. On the other hand, the increase in water temperature in this reaction is so slight that an ordinary thermometer will not measure it. The needle had a much higher temperature than the water but did not transfer much heat in the cooling process.

A large kettleful of boiling water contains more heat than a teacupful although both may be at the same temperature. The temperature does not depend on the size of the body but on the degree of concentration of the heat in it, that is, on the quantity of heat per unit mass, other things being equal. More ice could be melted with the water in the kettle than with the water in the cup because the water in the kettle can give off more heat.

At 26.6° C (80° F), ten pounds of water will melt more ice than one pound of water at 37.7°C (100° F); even though the ten pounds of water can evolve more heat, the pound of water is at a higher temperature. Thus, it is possible for an object to have a high temperature and give off little heat, to have a high temperature and give out a great deal of heat, to have a low temperature and give off little heat, or to have a low temperature and give off a great deal of heat.

It is axiomatic that a given body in a given state under given conditions must always contain the same quantity of heat and that different quantities of the same substance in the same state under the same conditions must contain quantities

1

of heat proportional to their several masses. An exception is the effect of shape on vibrational heat, normally not detectable. It is necessary to determine by experiment how the heat content varies for any given substance in different states or for different substances in similar states and how temperature variations affect heat content.

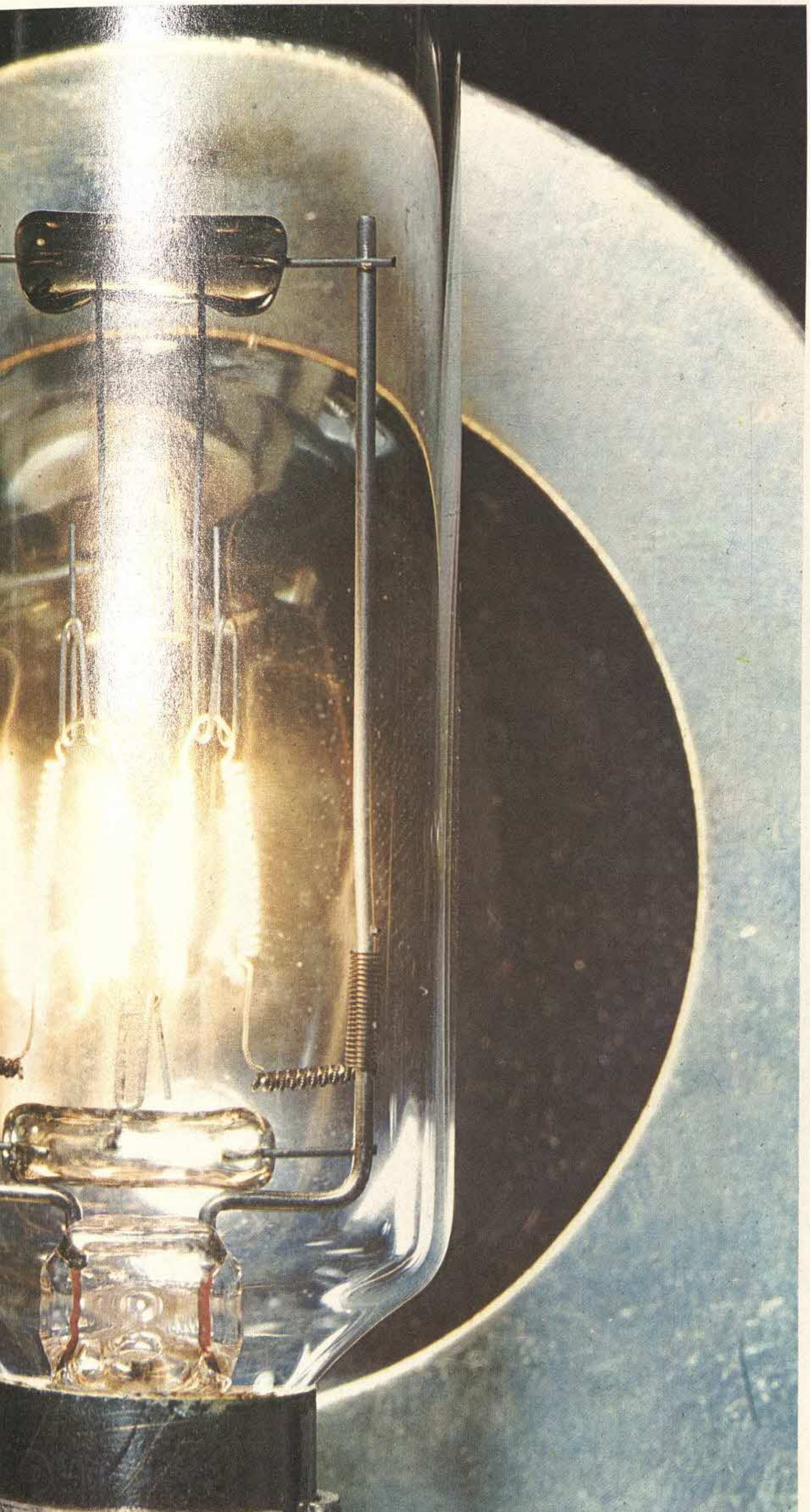
Physicists call such functions as temperature and quantity of heat intensive and extensive magnitudes. By intensive magnitude is meant the characteristics of the state of a body that do not depend on mass or volume (that is, temperature).

On the other hand, extensive magnitude refers to those states that depend on the quantity of matter involved.

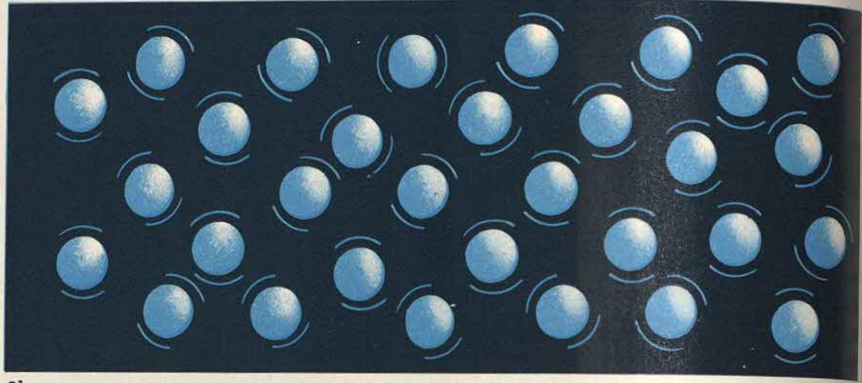
When two objects with the same properties and temperature are joined, the larger object that results will still have the same temperature as before. Similarly, two objects traveling at the same speed will not form a body traveling at twice the speed if they are joined. The intensive magnitude in each remains the same.

In the case of extensive magnitude, the results are entirely different. For example, if two bodies of the same weight are put together, the resulting body will weigh twice as much. When the two bodies contain the same quantity of heat, the result when they are joined will be a body with twice the amount of heat of either of the original bodies. Energy is another additive characteristic, and is thus an extensive magnitude.

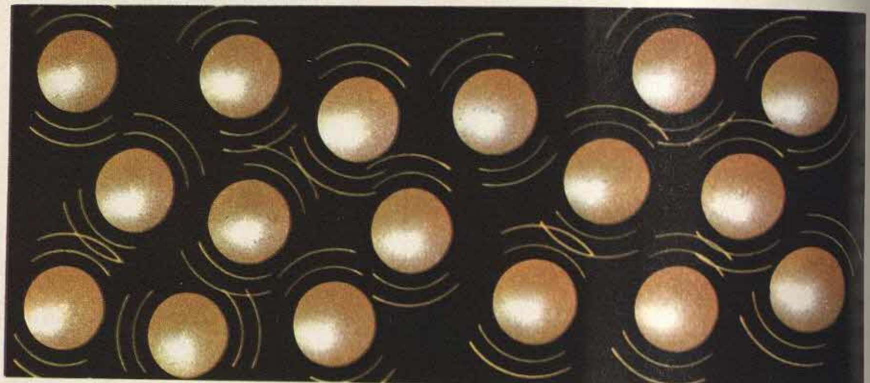
Thus, it can be said that temperature and quantity of heat are the intensive and extensive characteristics, respectively, of the thermal properties of the same body.



TEMPERATURE AND VOLUME—Although the filament of a light bulb attains a very high temperature, the quantity of heat will remain relatively small because the filament is small in size. The temperature, however, increases to a large degree (intensive magnitude).



3b



MEANING OF TEMPERATURE—All matter is made up of atoms in continual and somewhat disorderly agitation. In a solid, atoms oscillate around a fixed position, and collisions vary the speed and direction of these oscillations. The average speed of the atoms in a cold object (Illustration 3a) is quite low, but they move very rapidly in a hot object (Illustration 3b). Thus, temperature depends on the speed of agitation of the atoms in a particular object.

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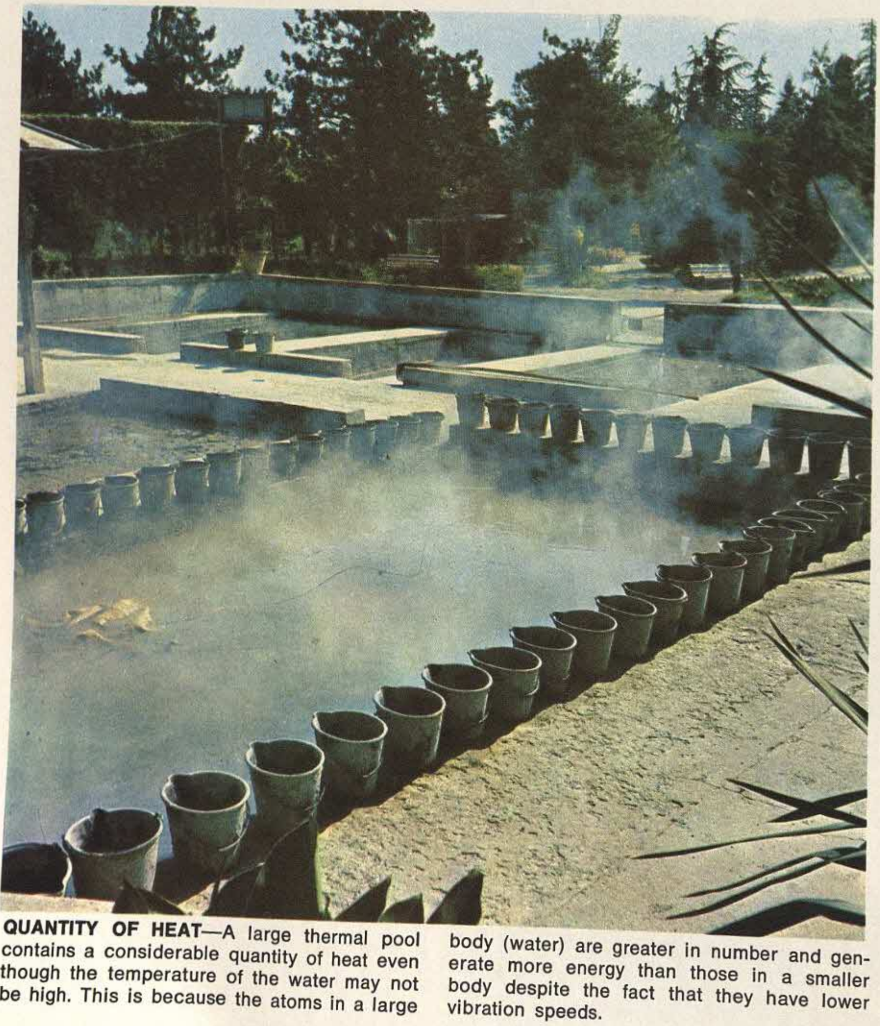

QUANTITY OF HEAT—A large thermal pool contains a considerable quantity of heat even though the temperature of the water may not be high. This is because the atoms in a large body (water) are greater in number and generate more energy than those in a smaller body despite the fact that they have lower vibration speeds.

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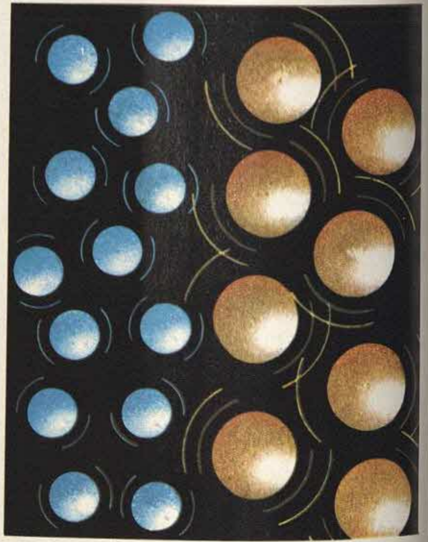

HOT AND COLD OBJECTS— In placing hot and cold objects together, the faster atoms in the hot object will collide with the slower atoms of the cold object and transfer energy to the cold object. This heating process is spontaneous and usually irreversible. The atoms of the cold object cannot move the faster atoms of the hot object in such collisions, which explains why heat never passes from a cold object to a hot one.

THE CONDUCTION OF HEAT

a natural but complex phenomenon

If a pot of boiling water is taken off the burner of a stove, the water will eventually cool to the temperature of the room. An ice cube outside a refrigerator will eventually melt, and the water will rise to the temperature of the room. Both examples show the propagation of heat, such a natural and spontaneous phenomenon that few persons give it much thought.

In intuitive language, the heat contained in hot bodies is propagated toward the environment, becoming dispersed in it; in the case of a colder body, the environment cedes heat to it and warms it.

Propagation of heat means simply that heat in a body will in time pass into some other nearby body, provided the second body is at a lower temperature. This poses three problems of physics: What is heat, how is it propagated, and what are the mechanisms by which it passes from one body to another? The answers are important to a large number of technical applications, but they involve some very complex problems. This article deals with the last two questions.

THE THREE FORMS OF HEAT PROPAGATION

Heat is propagated in three ways: by conduction, convection, and radiation.

Conduction is a form of heat propagation that occurs through a mass of a solid whenever a part of the solid is at a higher temperature than the remainder. Conduction also occurs in liquids and gases, but in conjunction with propagation by means of other mechanisms. In solids, heat and thermal energy are propagated without any movement within the body.

In convection, heat is transported by the movement of matter. For example, the coolant of an automobile engine moves from the engine block to the radiator, and the heat removed from the block is transported to the radiator by means of the coolant.

Heat propagation by radiation occurs without any movement of matter and can occur even in a vacuum. Radiant heat is characteristic of the way in which heat is transmitted from the sun to the Earth, from the flame in the fireplace to the person standing in front of it, and from the filament of an incandescent lamp to the surrounding environment.

When a hot body cedes heat to colder bodies in its vicinity, all three of these mechanisms—conduction, convection, and radiation—normally come into play. This article will consider conduction only. The more complex subjects of convection and radiation, the latter involving laws of optics and the theory of electromagnetic waves, require separate treatment.

STATIONARY AND TRANSITORY CONDITIONS

Because the study of conduction concerns the distribution of heat within bodies, solving a heat conduction problem requires determination of the temperature at every point within a body and at all instants of time. The heat distribution within a body may or may not vary with respect to time.

For example, suppose that boiling water at 100° C (212° F) is running through a long tube and that the temperature will remain constant. To ensure that the water will not cool while passing through the tube (because the external environment is at a lower temperature), the tube is covered with an insulating substance to prevent the heat from being easily propagated into the air, where it would become lost.

CONDUCTION—This type of heat transmission is typical of solid bodies. The worker shown must protect his hands with gloves; otherwise, the heat propagated along the handle of the instrument with which he obtains a sample of molten steel would burn his fingers.

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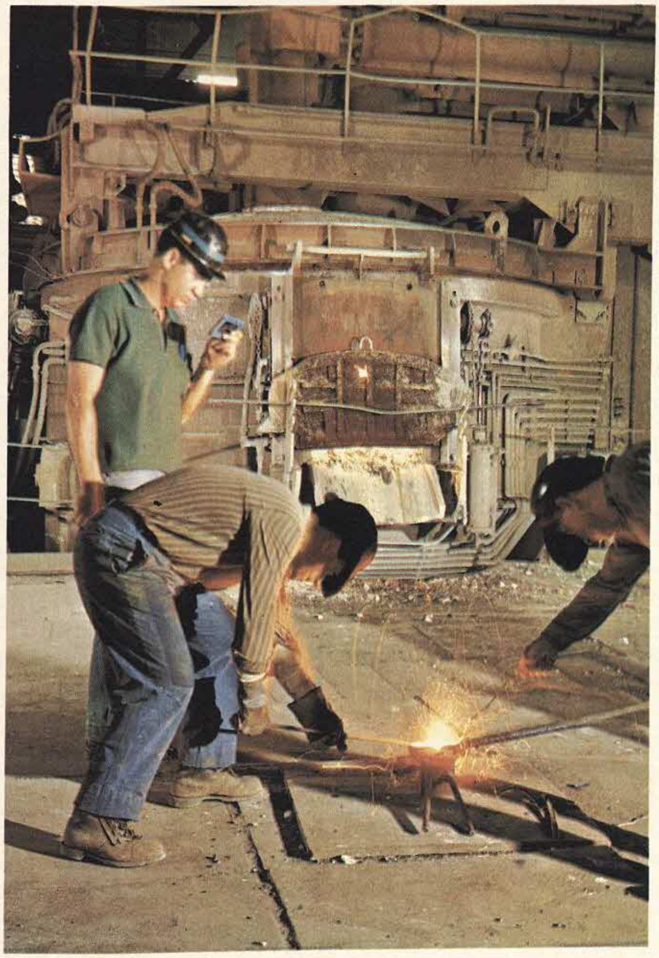
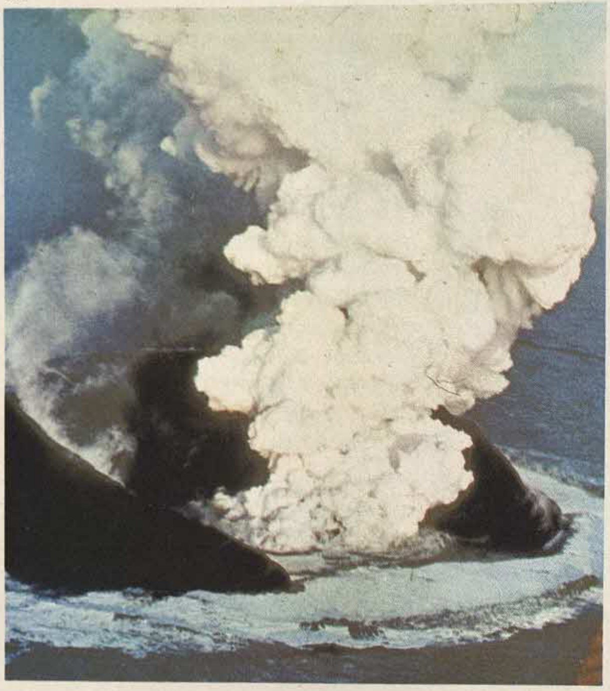


2a



CONVECTION AND RADIATION—The jet of steam that rises from Surtsey Island in Iceland (Illustration 2a) carries heat from deep inside the Earth into the atmosphere by means of convection. The foundry worker controlling the correct functioning of a furnace (Illustration 2b) holds a screen in front of his face to protect himself against the heat leaving the furnace by means of radiation.

2b

If the insulation is effective, the temperature measured at the contact surface between the insulating material and the tube will always be 100° C, while at the outer surface of the insulation, that in contact with the air, the temperature might be 20° C (68° F), the average temperature of the environment.

Determining the distribution of the temperature across the layer of insulating material is a particular problem in thermal conduction. Although heat continues to pass through the thickness of the insulating material from the inside to the outside, the temperatures within the insulating material do not vary and the temperature distribution does not vary with respect to time. This presents a condition known as a stationary condition.

If a copper bar is suddenly immersed in hot water, in the beginning every point of the rod will be at room temperature. The immersed part of the rod soon becomes heated and the heat is propagated along the rod.

Determining the way in which the temperatures are distributed within the bar at every instant after the immersion presents a problem that involves transitory conditions—conditions of temperature distribution that are destined to vary and will disappear. If the copper rod is left with one of its ends immersed in hot water for a sufficient time, an equilibrium will be reached; that is, the quantity of heat that enters at the immersed end will be equal to the amount that is dispersed by the parts that are exposed to the air. From that moment on the temperature distribution within the bar will not vary. The bar has now attained a stationary condition.

A more complex case is presented if the bar is immersed in hot water and the water is then replaced with ice. Alternating hot water and ice at short intervals produces a continuous variation of heat transfer within the bar and makes a stationary condition impossible. The temperature of the bar will vary continuously.

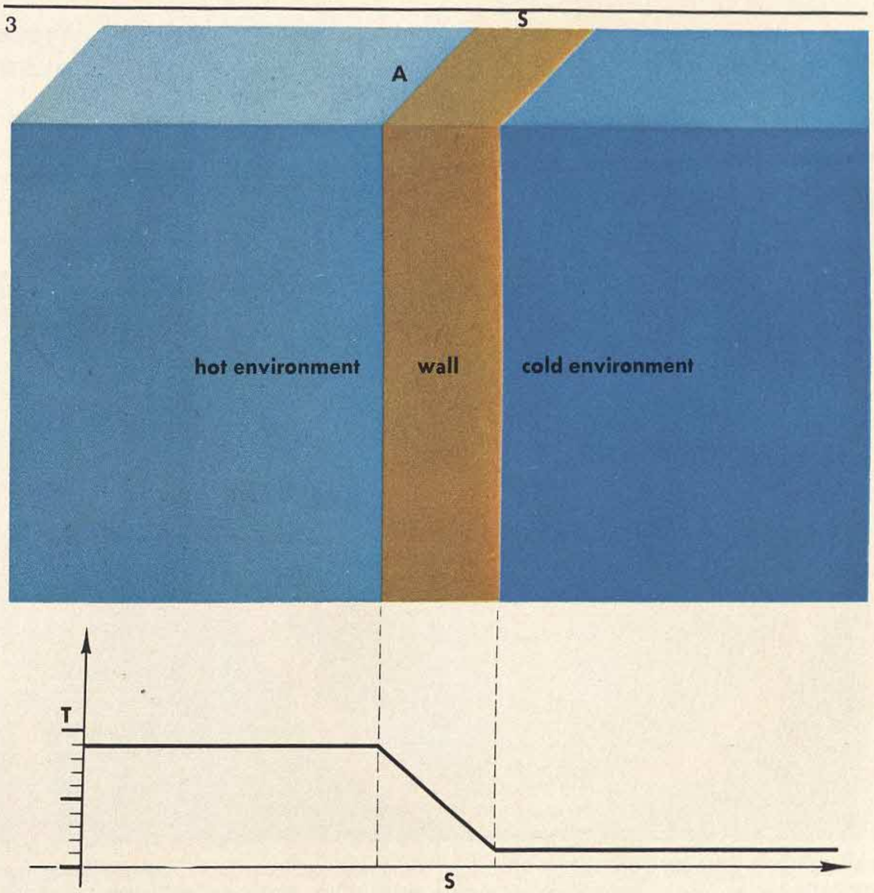
APPLICATIONS

Various applications both in pure and applied science require an understanding of thermal conduction.

Knowing the properties of matter from the point of view of heat conduction requires knowing certain characteristics that help explain the atomic structure of matter. For example, it is known that heat conduction depends on the percentage of free electrons within matter. Heat conduction is, therefore, an exterior and macroscopic effect—an effect that can be perceived by the senses—of an atomic property of matter that is not visible by direct observation.

To determine what thickness of insulating material should be used in the construction of a refrigerator requires knowing the heat conduction properties of the material chosen.

Before constructing a generator of thermal energy (such as a steam boiler with an oil-fired flame, or a nuclear reactor) the designer must know how the



THE SIMPLEST CASE: FOURIER'S WALL—The simplest case of heat conduction is illustrated above.

A wall of known thickness **S**, wholly made of the same material and extending to infinity in either direction, is brought to a certain temperature T_2—100° C (212° F), for example. How is the heat transmitted across this wall? The answer can be determined either by means of mathematical calculation or by means of experiment. Either method will confirm that the quantity of heat that crosses the wall in 1 second is proportional to the area **A** of the wall that is being considered and proportional to the temperature difference between the two faces, but is inversely proportional to the thickness of the wall. The quantity of heat that is transmitted is also proportional to a constant that depends on the characteristics of the material from which the wall is made. These properties of thermal transmission can be summarized by a formula. If the surface of the wall (shown by the dashed section) involved in the transmission is denoted by A, the formula is:

$$Q = KA\frac{T_2 - T_1}{S},$$

where Q is the quantity of heat transmitted and K is the constant that depends on the thermal transmission characteristics of the wall.

The graph represents the temperature variations within the wall. Because the temperature decreases uniformly from one face of the wall to the other, the corresponding part of the graph is a straight line. This means that the temperature variation in stationary conduction is a very simple one.

heat is conducted across the materials that separate the flame from the bodies that must be heated—in the case of the boiler, the metal tube that separates the flame from the water to be vaporized. This determines the temperature drop that must exist between the heating agent and the body to be heated and, consequently, the material that must be used for constructing the tube.

The problem of knowing the heat distribution within a solid is analogous, at least from the mathematical point of view, to the problem of knowing how an extraneous substance is diffused within a solid.

THE COEFFICIENT OF CONDUCTIVITY

Consider a series of various walls, each 1 cm thick and each made of different materials. One face of each wall is kept in contact with boiling water, the other in contact with ice. The quantity of heat that is propagated across, for example, one square decimeter of each wall will depend on the characteristics of the material from which it is made and is measured by a particular value of the coefficient *K*. This coefficient is a measure of the heat conductivity of the material.

Some materials are good conductors of heat; others are good insulators. The value of the constant *K* generally measures the number of calories that pass through 1 cm² of a wall 1 cm thick in 1 second when there is a temperature difference of 1 C ° between the two faces of the wall.

Table of Coefficients of Conductivity *K*

silver	1.1
copper	0.92
aluminum	0.49
cork	0.0001
expanded polystyrene	0.00007
wood	0.0005
water	0.001
nitrogen	0.00006

Water and gases have a very low thermal conductivity; however, before they can be used for heat insulation purposes it is essential to take precautions that will prevent the heat from being propagated by means of mechanisms other than conduction.

All foamy substances are poor conductors of heat because only very small quantities can be propagated through the small thickness of the membranes that constitute the walls of the cells or through the air contained within these cells. This air is immobilized and cannot, therefore, transmit heat by convection. This accounts for the very low conductivity of porous materials such as sponge, pumice, and expanded polystyrene, all of which have been expanded by means of a gas that has formed minute bubbles dispersed throughout the mass.

KIRCHHOFF'S LAWS | the emission and absorption powers of a body

When the light emitted by a star or a nebula is analyzed in a spectroscope—a device that disperses light into a spectrum, according to the wavelengths of the light—many phenomena occurring within the star or nebula are revealed—for example, the pressure of the gas in these distant bodies. This pressure is found to be extremely small—less than

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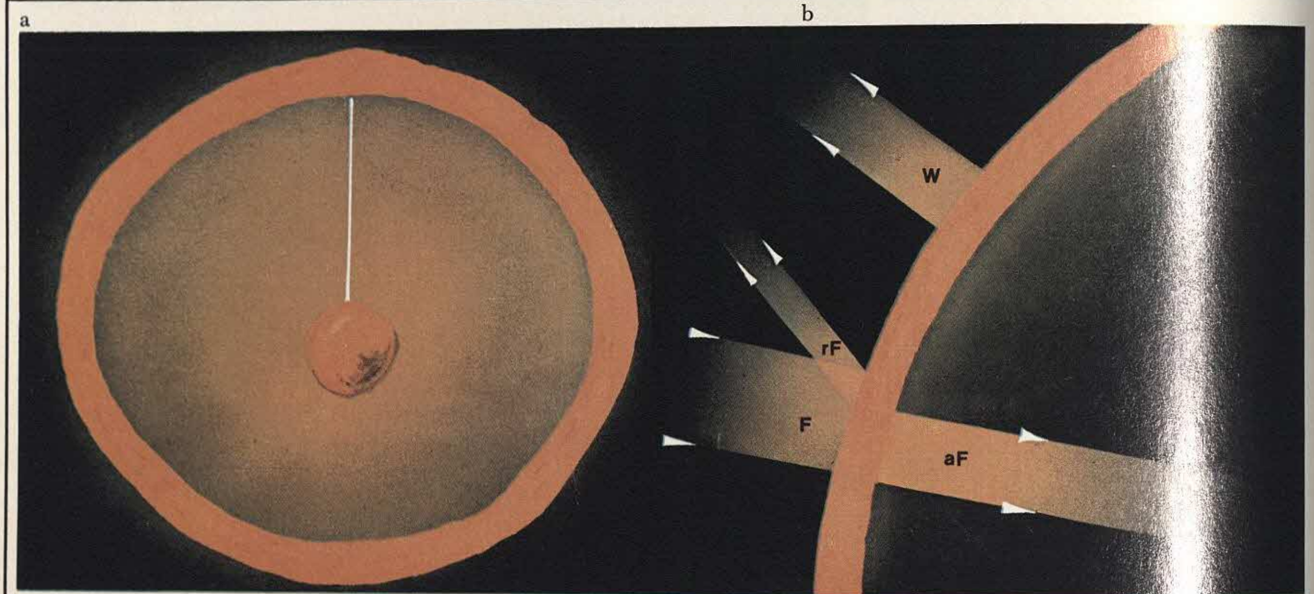

A BODY IN A HOLLOW CONTAINER—To demonstrate the equality of the emission and absorption power of a body, an object is suspended within a hollow container by a thread that cannot transmit heat energy; the object is, therefore, completely isolated from the walls of the container (Illustration 1a). If the container is now brought to a higher temperature, the temperature of the suspended object also increases—and no matter how much the temperature of the container is raised, the suspended object will eventually have the same temperature as the wall of the container. Of course, some time will elapse before a temperature equilibrium is reached between

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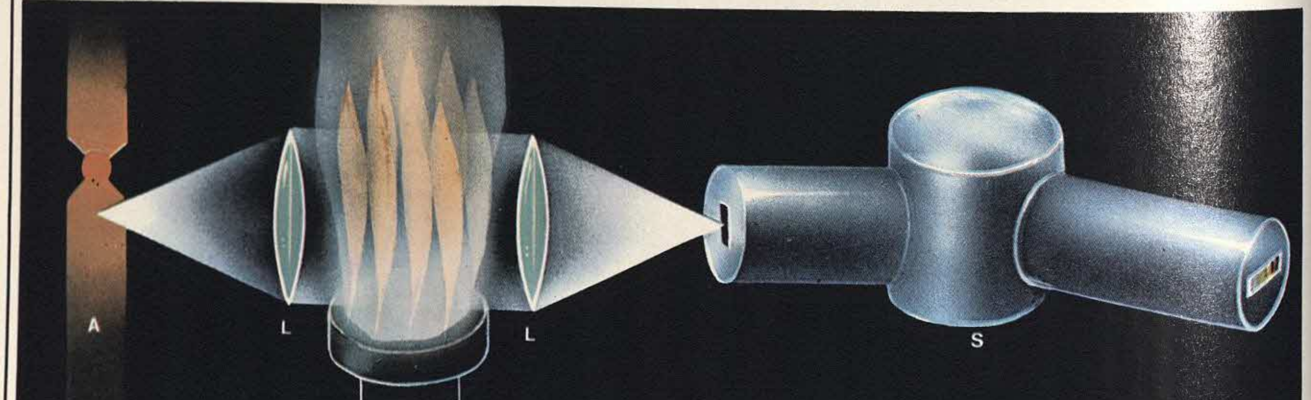

KIRCHHOFF'S EXPERIMENT—This illustration depicts a famous experiment conducted by Kirchhoff to show that, at a constant temperature, a body absorbs the same radiations that it emits. A voltaic arc **A** is formed between two electrodes, which will become highly incandescent near the spark gap because of the flow of current. A lens **L** collects the light emitted by the arc and focuses it into the intake that in a thoroughly evacuated air chamber on Earth; in stars and often in nebulas it is also possible, through spectroscopy, to determine differences in pressure and temperature within the layers that can be directly observed through optical instruments.

The laws of physics that make these observations possible were formulated by a German physicist, Gustav Robert Kirchhoff, in the 1860s. Kirchhoff made a general analysis of the problem of the emission of heat and light from various sources—and the laws he formulated apply not only in astronomy, but also in any field involving the transmission of heat energy by radiation. To Kirchhoff belongs the credit for enunciating a complete account of spectrum analysis and establishing the method on a solid basis. Kirchhoff was the first to explain the Fraunhofer lines.

RADIATION AND MATTER

Radiation phenomena include all phenomena resulting from the emission of energy in the form of electromagnetic waves, such as the energy emitted by an incandescent body because of the motion of its component atoms or molecules. Experiments show that any body becomes luminous and emits visible rays of red light, if its temperature is raised to about 500 to 550° C (932 to 1,022° F). At lower temperatures, these bodies emit infrared radiation, which has the same characteristics as light but has longer wavelengths.

One of Kirchhoff's laws states that the power of a body to emit radiation is the same as its power to absorb that radiation at the same temperature. Under this law, it is understood that absorption power means the quantity of energy absorbed in unit time by a unit of surface of the body receiving the radiation; and that emission power means the radiant energy emitted in a unit time by a unit of surface of the body. These magnitudes can be proved equal. In another experiment to prove one of Kirchhoff's laws, a body is shown to emit those kinds of radiation that it has the power to absorb, providing that other conditions, particularly temperature, do not change.

the object and the container—but it is always eventually reached. In practice, it has been found that no object can remain indefinitely insulated from the radiant heat of its environment.

If a detailed examination is made of a part of the surface of the suspended object, shown greatly magnified in Illustration 1b, it appears that the flow of energy $\mathbf{F}$ strikes the surface and is partly absorbed $\mathbf{aF}$ and partly reflected $\mathbf{rF}$ back to the wall of the container. If $\mathbf{F}$ is unity (1), then $r + a = 1$. It has been assumed that the suspended object is not transparent; if it were transparent, the equation would not hold, inasmuch as part or all of the radiation would pass through—be transmitted by—the object.

Each part of the surface of the suspended object will absorb a portion $\mathbf{aF}$ of the energy it receives; because the object is hot, it will also emit an amount of energy $\mathbf{W}$. When an equilibrium of temperature is reached, as described above, the amount of energy emitted equals the amount absorbed; that is, $\mathbf{W} = \mathbf{aF}$—or, to transpose the equation, $\mathbf{F} = \mathbf{W}/\mathbf{a}$. This is an expression of Kirchhoff's law, which states that the ratio of the radiation emitted per unit of surface area and the absorption power is constant, and depends solely on the temperature (and not on the composition) of the body.

slit of a spectroscope, which disperses the light according to wavelength into a continuous spectrum. In the illustration, however, a gas flame has been interposed between the arc and the spectroscope, in such a way as to cover the incandescent light of the arc. The flame emits a yellow light, caused by the presence of sodium in the vapor being burned. Although the flame continues to appear transparent to the eye, it will cause a black line to appear on the continuous spectrum at the point where the yellow characteristic of sodium would normally (without the interposition of the sodium-charged flame) appear. This line is caused by the absorption of the radiation with a frequency equal to that emitted by sodium.

Kirchhoff's experiment is frequently performed in laboratories that carry out chemical analyses by means of absorption spectroscopy of atoms. The spectrum of the test element is used to absorb the line or lines within the spectrum in the spectrophotometer. The more abundant this element is in the sample, the more of it is absorbed in the spectrum.

3

APPLICATIONS — Kirchhoff's discovery soon found important applications. It became possible, for example, to understand why the stars, including the sun, display absorption spectra; in fact, it became clear that the core of a star emits radiations from layers at extremely high temperatures; whereas the outer layers, closer to interstellar space toward which the radiation is directed, are colder and strongly absorb part of the radiation emitted by the inner layers. The diffuse nebulas, on the other hand, have an almost uniform temperature and, therefore, display only emission spectra. It therefore became possible to use spectroscopy to determine whether a celestial object is a star or a diffuse nebula: if it has an emission spectrum, it must consist of diffuse gases and be a nebula; if it has an absorption spectrum, however, it must be a star or group of stars. Thus it was no longer necessary to observe these objects directly through telescopes; spectroscopic evidence was enough.

Illustration 3a is part of the spectrum of the star Deneb (α Cygni), the continuous background of which is broken by absorption lines of the elements found in the star's atmosphere, which absorb part of the light emitted by the underlying layers. Only stars with an atmosphere hotter than the underlying layer, or photosphere, emit a line spectrum.

Illustration 3b shows the process that leads to the inversion of the lines in a stellar atmosphere such as that of the sun. In the lower left part of the illustration, the light blue area represents the ionized matter that emits the continuous spectrum. Above this, whenever the temperature and pressure are such as to permit the gas to be no longer ionized, is the transparent atmosphere. However, this transparency disappears in correspondence to those wavelengths characteristic of radiations that the elements in the stellar (solar) atmosphere are themselves capable of emitting. A very small layer of stellar atmosphere, of the order of a few hundred meters, can produce the absorption detectable from the Earth. This layer, called an inversion layer, transforms an emission spectrum into an absorption spectrum. The graph on the right side of the diagram shows the separation of the photosphere **F**, which marks the border between the ionized and non-ionized matter, and the inversion layer **I**. As the graph shows, the temperature **T** falls very rapidly in the inversion layer as the distance increases above the photosphere.

Illustration 3c is a photograph of the gaseous Trifid nebula (M20) in the constellation of Sagittarius. Its constituent gases are all in a state of extreme rarefaction. Nevertheless, most of the atoms are not ionized, and most of the emitted radiation is produced by the atoms in the form of a few characteristic radiations. The nebula easily absorbs energy from outside but emits only a few characteristic wavelengths; it behaves, therefore, like a body with a high coefficient of absorption but only a small coefficient of emission.

Such a body was said above not to be capa-

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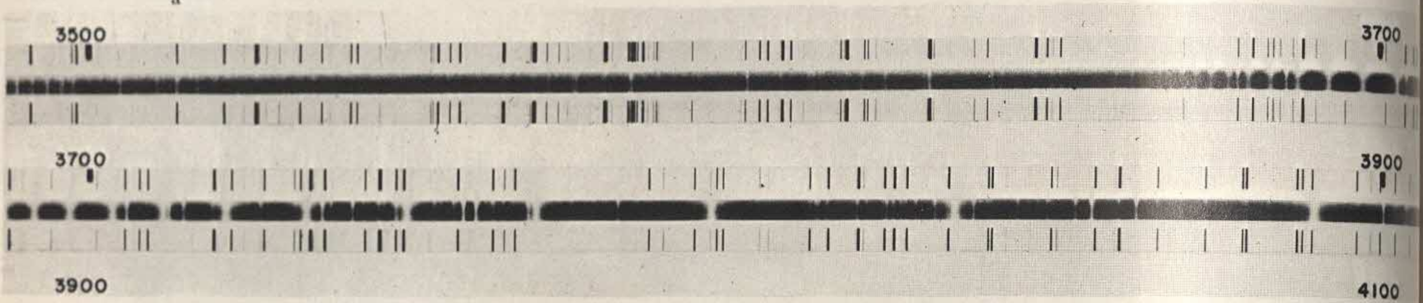
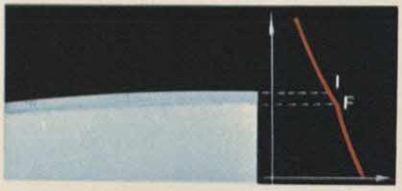


ble of existing, at least when the radiation it exchanges with the environment (as the hollow container in Illustration 1) is thermal energy and has a continuous spectrum. A nebula, however, can participate in nonthermal exchanges of energy, and this causes the disparity between emission and absorption. The temperature of the nebula, therefore, rises to tens of thousands of degrees. Yet even in the case of a nebula, an equilibrium is eventually reached; the disparity between emission and absorption causes an increase in temperature, but the emission continues to increase with the temperature until it becomes equal to the absorption. In these conditions of equilibrium, the temperature of the nebular gas may exceed that of the environment around the nebula. This does not contradict the principles of thermodynamics, because a nebula absorbs energy by means of collisions with particles of interstellar dust and interactions with the magnetic fields present in space.

The upper part of Illustration 3d shows the slitless spectrum of a planetary nebula. The lower part shows the same spectrum obtained through a slit in the spectroscope.

b



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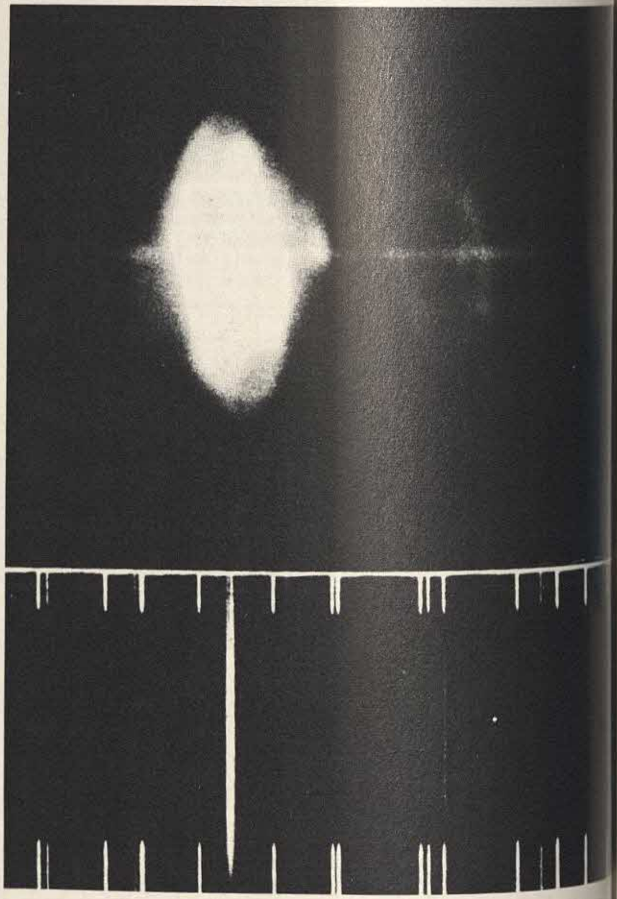


EXAMPLES OF THERMAL CONDUCTION

why walls protect man against the cold

Shelter has been a basic need of man since very early times. Remains of the Peking man—the best-known example of *Homo erectus*, the first true man—were found in a cave in which he sought shelter from the bitter cold during a time of glacial advance, perhaps a half-million years ago. The limestone walls of the cave provided an insulating barrier between the cold air outside and the warmer air inside. The walls of a modern home serve the same purpose, often incorporating insulating material especially chosen for its low thermal conductivity.

The purpose here is to present examples of thermal conduction in which heat is transmitted through bodies of various forms, and examples of transitory thermal phenomena—those cases in which a body is heated at a certain instant and the situation is then caused to change rapidly.

1

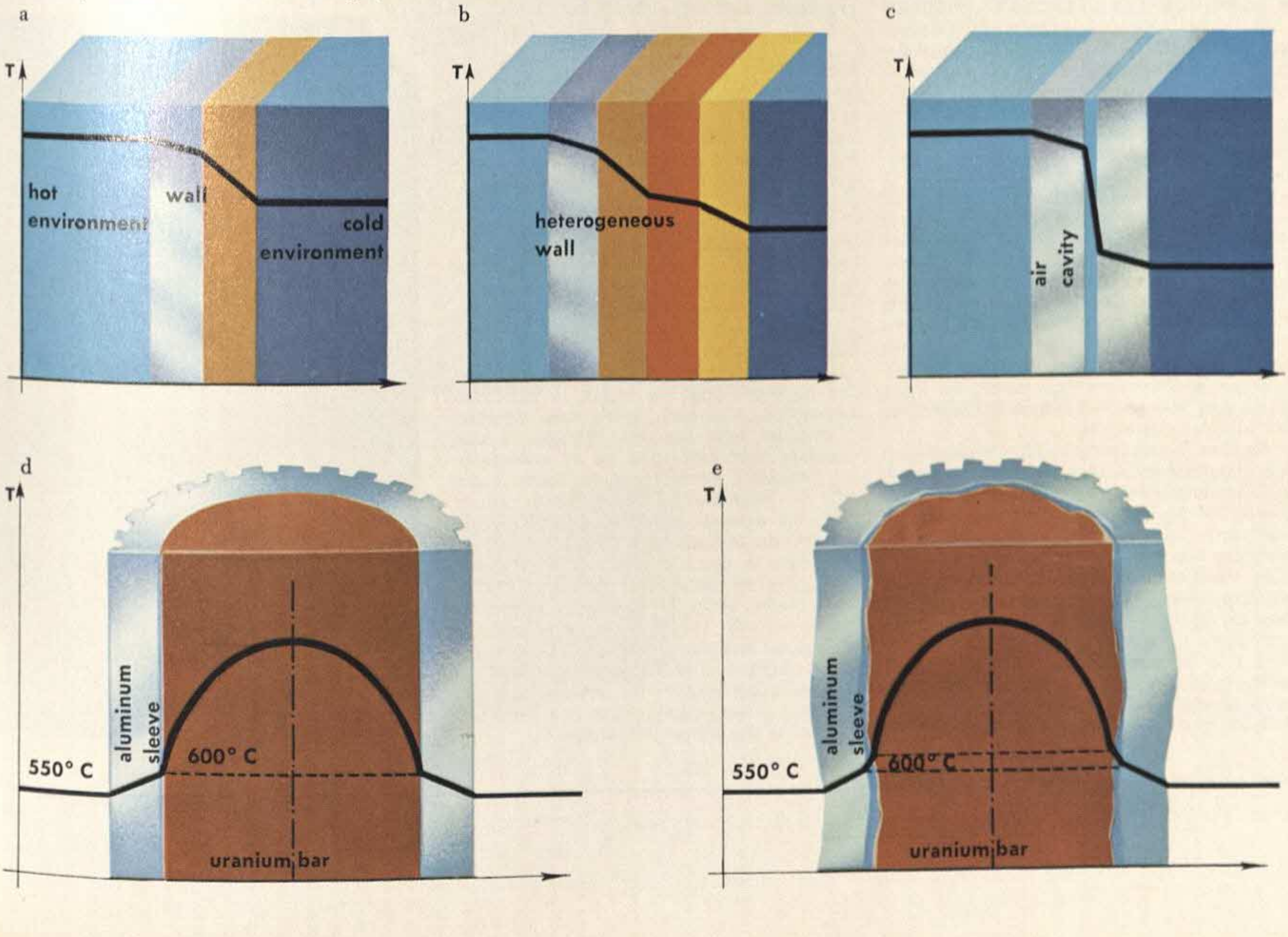
THE CASE OF THE HETEROGENEOUS WALL—Heat is propagated through a wall according to a certain law when the wall is made up of a homogeneous material and the two faces are maintained at different temperatures. In particular, the temperature at different depths within the wall decreases in a linear manner from the hotter to the colder face. In the case of Illustration 1a, the wall is made up of two different substances, one a good conductor of heat and the other a poor one. Each substance makes up half the thickness of the wall. The illustration shows how the temperature varies within the wall. The left half of the wall has the greater conductivity, and in this part the temperature decreases only slightly. In the right half there is a considerable decrease in temperature between one face and the other. This means that the conducting material on the left, at least for the purposes of heat insulation, behaves almost as if it did not exist.

In the case of a wall made up of several layers of material (Illustration 1b), each of which has different heat-conducting properties, the temperature will fall in several stages, with each stage corresponding to one homogeneous layer of the wall. When one of these layers is a much better insulator than the others, the greater part of the temperature drop will occur within this layer.

A real wall with a thin air cavity (Illustration 1c) is a particular case of the previous example. The thin layer of air conducts the heat much less readily than do the solid parts of the wall. The layer of air is, therefore, a great obstacle to the propagation of heat.

Illustration 1d shows a transmission phenomenon in the case of the fuel element of a nuclear reactor for the generation of electric power. The fuel element consists of a uranium cylinder that develops heat while the reactor is in operation. This heat must be propagated across the aluminum sleeve (other metals and alloys are also used), which prevents the radioactive substances formed within the cylinder from reaching the outside. In a new fuel element the aluminum sleeve almost touches the uranium, and the heat is easily propagated from the uranium to the water flowing past the outside of the sleeve. The water absorbs the reaction heat, boils, and is transformed into steam. In order to keep the outer face of the sleeve at a temperature of 550° C (1,022° F), for example, the uranium in contact will be at 600° C (1,112° F). The variation of the temperature within the fuel element is shown.

After the reactor has been in operation for some time—during which the uranium and the sleeve have undergone heating and cooling innumerable times—the two elements will become distorted and no longer in perfect contact with each other (Illustration 1e). If the reactor is to continue supplying the same power, the outer surface of the aluminum sleeve must remain at a constant temperature. Because there is no longer a perfect contact between the aluminum and uranium, the temperature of the uranium must now be greater than before. In this case the uranium may become damaged; it may crumble or become even more distorted, thereby causing the aluminum sleeve to break. All this occurs because the lack of contact between the uranium and the aluminum causes a great temperature drop between the inner and outer parts of the fuel element.



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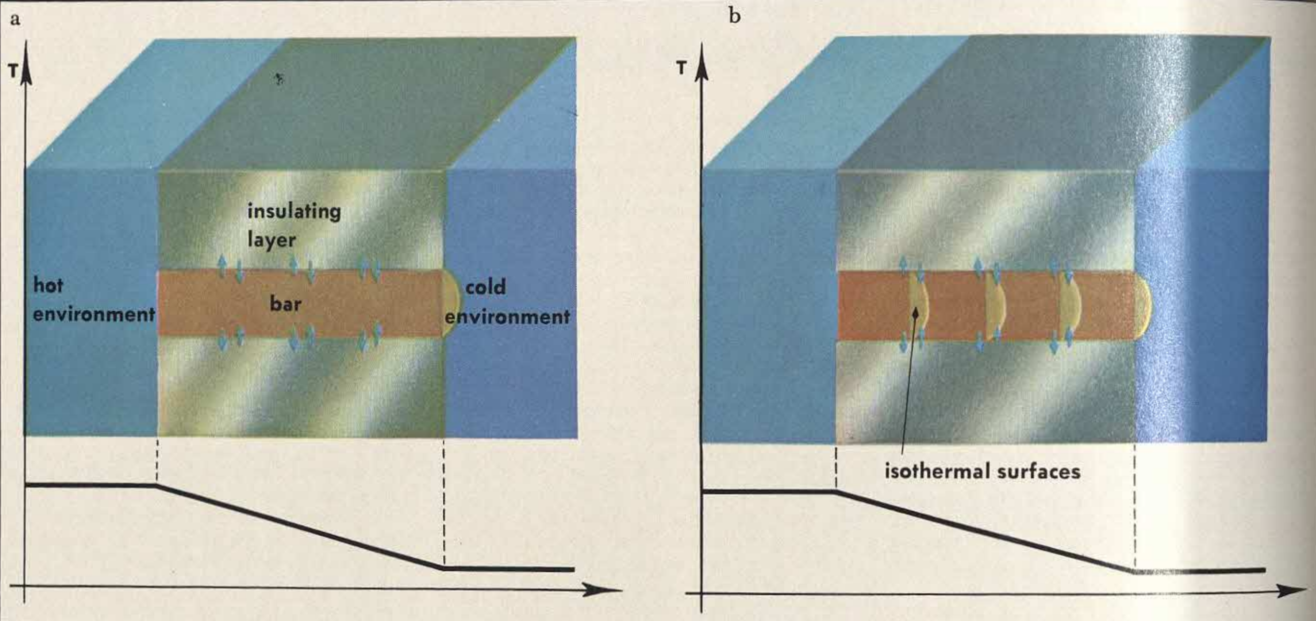


3

A MORE COMPLEX STATIONARY PROBLEM—Illustration 3 shows how complicated a problem becomes when the geometric form of the body within which the heat is propagated is no longer as simple as those shown previously.

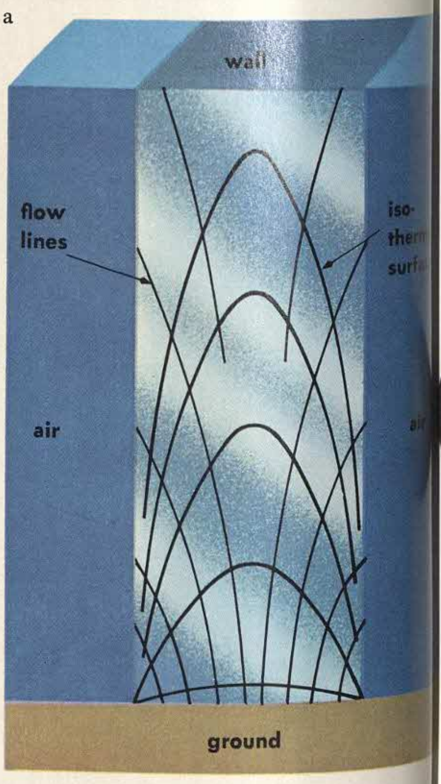
In the case of a wall standing on the ground and being supplied with heat through the ground (Illustration 3a), suppose that the temperature of the base is maintained at 10° C, while the temperature of the two faces, which are in contact with the air, is 0° C. The calculations required to determine the temperature variations within this wall are far more complex than they were in the previous case. However, the solution can be shown by drawing lines representing the isothermal surfaces and lines along which the heat will flow. These lines will be perpendicular to the surfaces. The heat is propagated from the base toward the faces of the wall from which it is then dispersed into the external environment.

Another complex mathematical problem that has important applications is that of a tube in an insulating sheath (Illustration 3b). Suppose that a hot liquid flows through the tube and maintains it at a constant temperature. To ensure that this heat does not escape to the outside, the tube is covered with a sheath of insulating material. The problem is to determine how the heat is propagated within this sheath, expressing the answer in terms of the temperature drop between the inside and the outside of the sheath, the insulating properties of the material, and the thickness of the material. The formula that expresses the amount of heat propagated across the sheath is:

$$Q = \frac{2\,LK\,(t_2 - t_1)}{\log b/a}$$

where Q is the quantity of heat transmitted, a is the internal radius of the sheath, b is the external radius, L is the length of the sheath, K is the coefficient of conductivity, t_1 is the temperature on the inside of the sheath, and t_2 the temperature on the outside of the sheath. Q is inversely proportional to the logarithm of the ratio between the external and internal diameters of the sheath. This means that the greater the thickness of the insulating sheath (the internal diameter remaining constant, as in case b′), the greater the insulation. Note, however, that the transmission does not decrease in inverse proportion to the thickness; the thickness must be tripled to halve the conduction. Alternately, if the inner diameter is reduced while the outer diameter is kept constant, there will again be an increase in the protective efficiency of the sheath (case b″); the increase will depend on the ratio of b/a—the external and internal radii.

A cylinder heated at the base (Illustration 3c) is a case in which one end of a bar made of conducting material is in contact with a heat source, while the rest of the rod is exposed to cold. The heat enters at one end of the rod and leaves through the entire external surface. The temperature within decreases exponentially—the decrease between any pair of equidistant points is a fixed proportion of the higher temperature.



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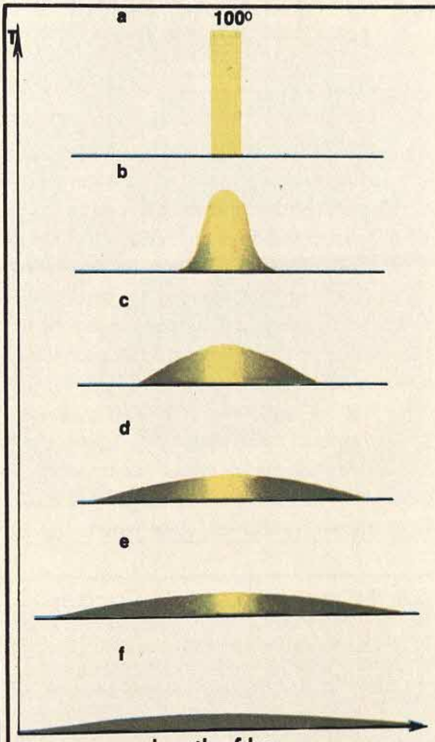


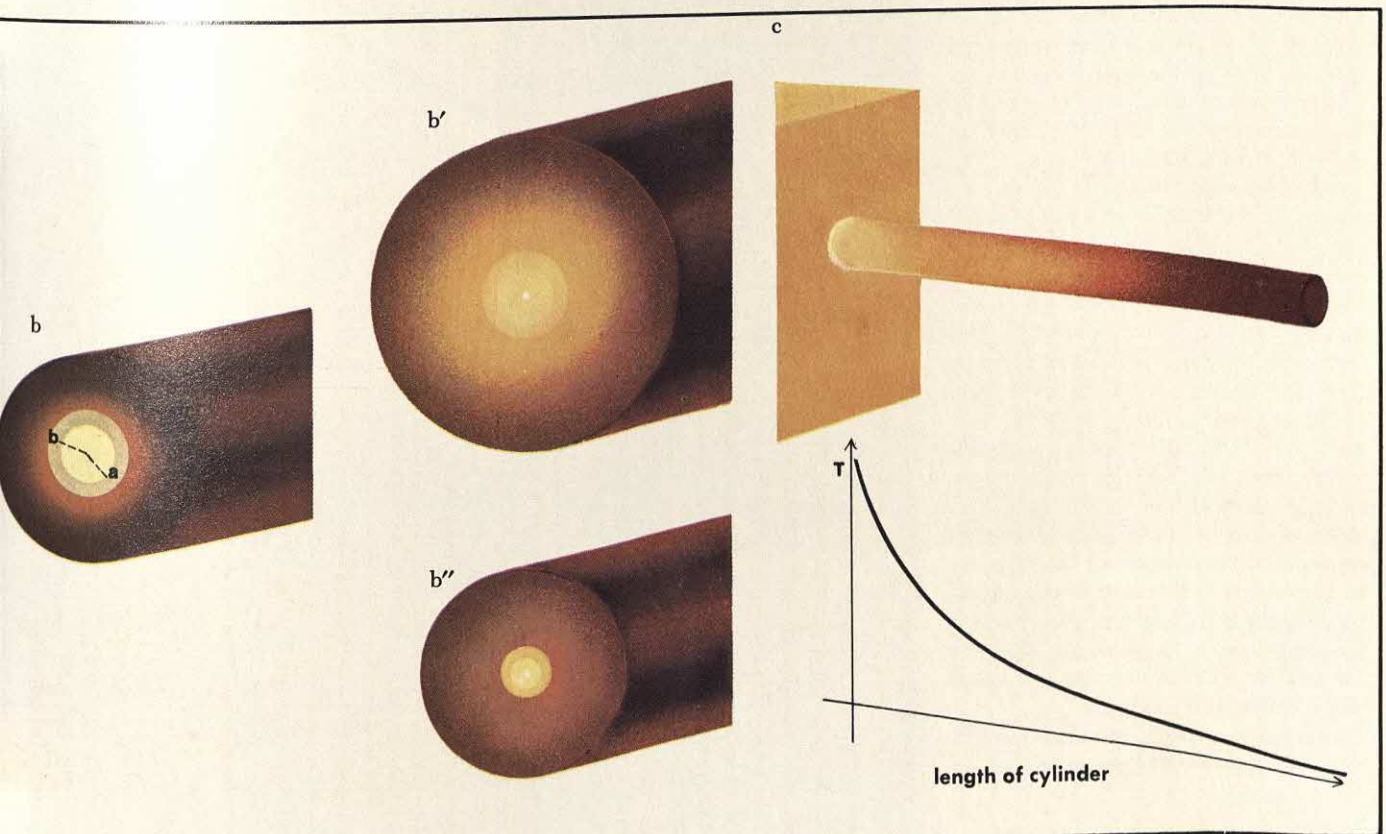
A NONSTATIONARY CASE—A most difficult case of heat propagation is that involving a body whose points are initially at a certain temperature, but later at temperatures that vary with respect to time. This is the case of a round bar that is thermally insulated from its environment and whose center is instantaneously brought to a temperature of 100° C, the rest of the bar remaining at 0° C. The problem of ascertaining the temperature distribution at later instants is complicated because the situation is continually variable with respect to time.

The illustration shows how the temperature distribution evolves with respect to time. At the instant **a** the temperature is very high at the center of the bar, but remains at 0° C over the remainder of the bar. In **b, c, d, e,** and **f,** a progressive temperature decrease occurs. At first the temperature falls very rapidly as the heat distributes itself in a small space around the central point. Then the temperature changes gradually from the maximum value to smaller values toward the ends of the bar, but the fall is now less rapid. At the same time there is a lowering of the temperature at the center. The heat that causes a temperature rise along the whole length of the bar—although only to a low temperature—is quantitatively the same in this final stage of the heating process as the amount of heat that was originally stored in a very small length at the center of the bar.

This is one of the least complex cases of heat propagation that varies with respect to time. More complex cases cannot always be resolved in a rigorous mathematical form; approximate solutions must be found. In the case of complex forms and complicated variations with respect to time, the problem becomes so difficult that even the fastest electronic computers require several days to solve it.

THE CASE OF AN INSULATED BAR—This illustration presents the so-called wall problem from another point of view. In this case (Illustration 2a) the subject is not a wall, but a round bar whose ends are at two different temperatures and whose sides are insulated by a layer of insulating material that is assumed to be perfectly efficient. What happens in the bar is equivalent to what happens in a cylinder built into and across a wall. In fact, within this cylinder the heat can only become propagated in the direction of its longitudinal axis, because the walls of its lateral surface are in contact with other points of the insulator that are at the same temperature. The heat cannot, therefore, be propagated in the direction indicated by the small blue arrows.

In Illustration 2b the bar has been cut by planes in such a way as to indicate surfaces where all the points will always have the same temperature. Such surfaces are called isotherms or isothermal surfaces. The isothermal surfaces in the case of the bar are represented by planes drawn parallel to the two ends of the bar.



CONVECTION CURRENTS

the transfer of heat by fluids

Everyone has observed what happens to water as it is heated to the boiling point. The water rises from the bottom of the vessel, where it is closest to the flame, and reaches the surface; there, coming in contact with the cooler air and forming vapor, it is cooled and falls back to the bottom of the vessel once more. These vertical (up-and-down) movements that occur in a volume of heating water are known as convection currents (convection is derived from the Latin *convehere*, "to carry along," similar to the English "convey"). As a matter of fact, the water rising in the heated vessel carries the heat from the bottom to the top. This is an application of Archimedes' principle, according to which a fluid (liquid or gas) increases in volume and decreases in density as its temperature rises; it, therefore, rises above the denser fluids that surround it.

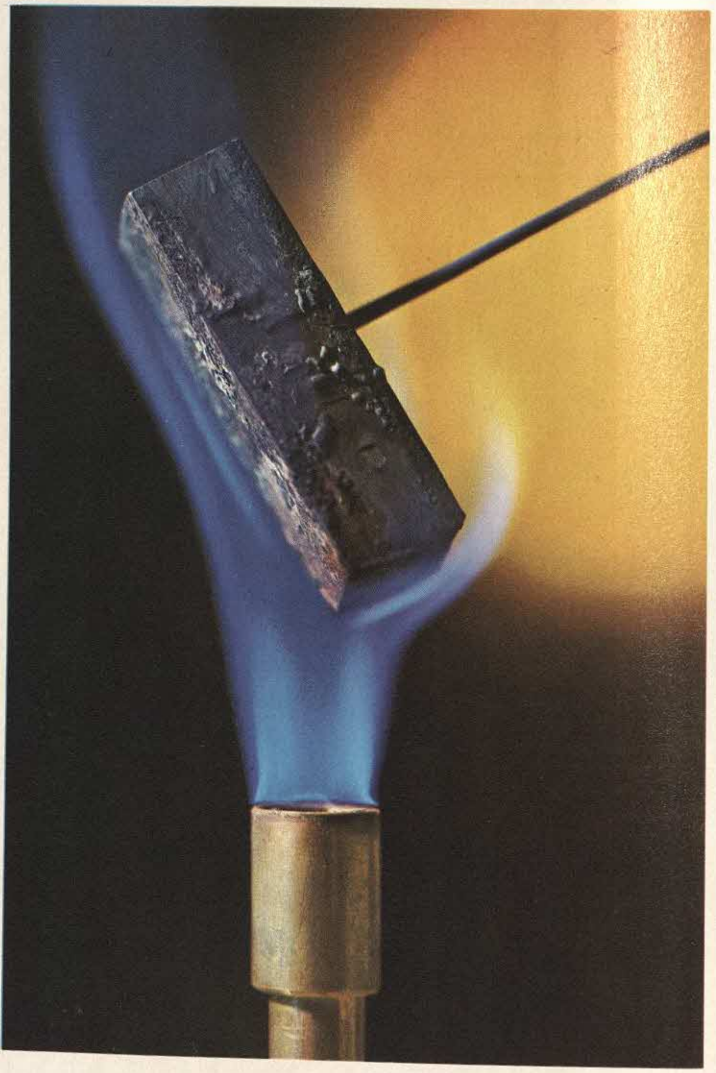
Nature affords many examples of convection. The relatively higher temperatures of the ground in the spring and summer cause the lower layers of air to rise until, at a certain altitude, they become cool, and the moisture particles they contain are condensed. This kind of convection current thus accounts for the formation of the beautiful cumulus clouds that look like tufts of cotton. Similarly, convection currents, caused by temperature changes in bodies of water, result in movements of layers of water in many lakes and even in the sea at certain points along the shore.

An impressive natural example of convection is the transfer of energy within the stars, including the sun. The energy that eventually is radiated into space comes originally from the relatively small central core of the star. In order to pass from this core, for a distance of more than 500,000 mi (the radius of the sun is 432,000 mi; that of giant stars more than 7,000,000 mi), to the relatively "cool" surface of the star, the energy must be transferred in various ways. The most important of these ways is through convection. The surface of the stars—as can be observed on the sun—is agitated by a continual explosion of gases, which are analogous, on a grandiose scale, to the bubbles that form on the surface of water boiling in a saucepan.

Technology and the practical applications of science also present numerous examples of convection. A most obvious example is the chimney, the visible exit of the heated air produced by convection. A central heating system produces convection currents in order to convey hot water through pipes to various floors of a building. There are many variations in the method of transferring the heat from hot water, steam, or electric resistors to the space to be heated. Combination systems that use steam and hot water with hot air are known as split systems. Many public buildings are heated by hot-blast systems in which steam generated in a boiler flows to large banks of heat-transfer surfaces over which air is blown by large fans; the warmed air is supplied to rooms through ducts. This type of system often is used for air conditioning, the heat-transfer surface being fed cold water in summer and steam in winter. Even the separation of isotopes (for example, uranium-235 from uranium-238) may be accomplished by setting up convection currents in a vertical column by suitable heating; such an application requires profound knowledge of the laws that govern these movements and the phenomena they produce. However, it is possible to perform some simple experiments to demonstrate the existence of convection currents.

CONVECTION CURRENTS IN LIQUIDS—A convection current can be produced in water by local heating, such as by the immersion of a block of heated metal in cold water. First, the metal is heated over a flame (Illustration 1a). Then the block is suspended by the wire and immersed in the liquid (Illustration 1b). At first, the temperature of the block of metal will fall rapidly, because of its contact with the cold water, but it will take a long time before the temperature of the block falls to that of the water. Before this occurs the water itself will become heated, and will rise from the bottom of the beaker toward the surface. The rising convection current is visible because the refractive power of water diminishes as its temperature rises; an incident ray of light will not cross the beaker in a straight

1a



1b

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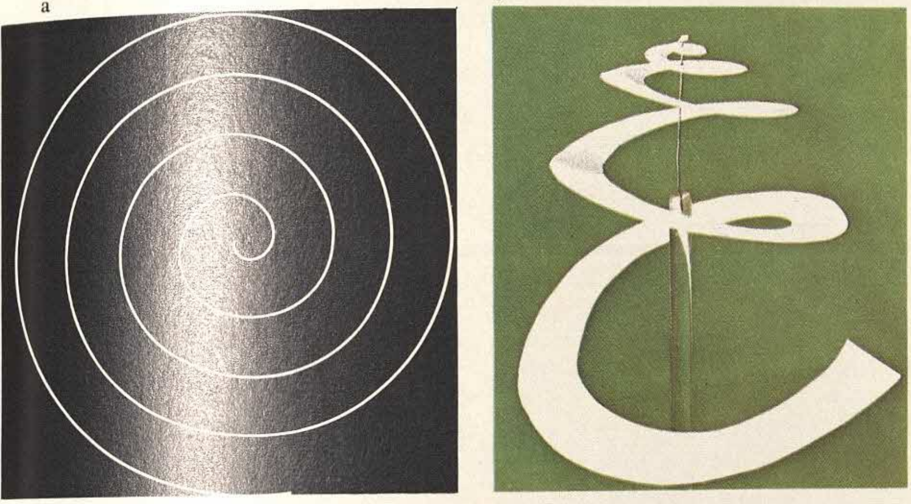
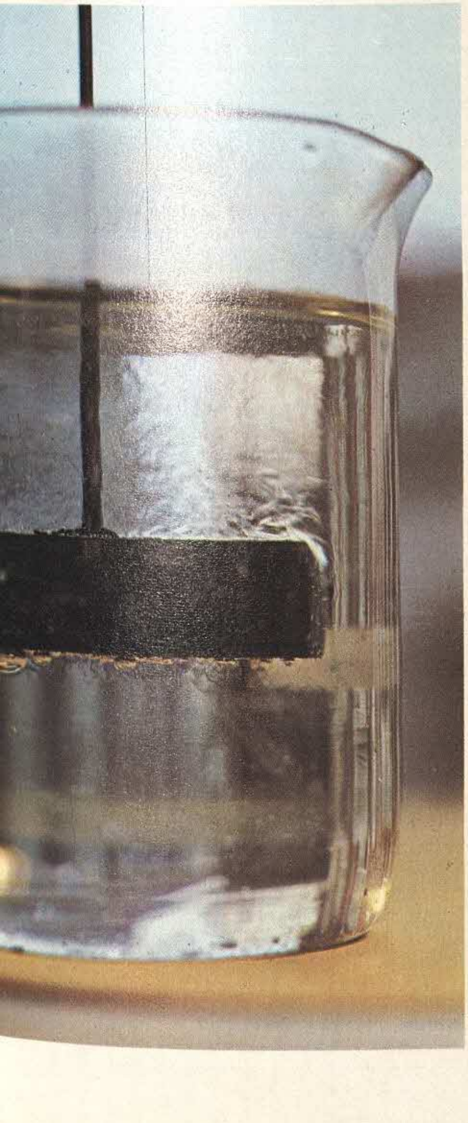

a

b

CONVECTION CURRENTS IN AIR—A similar lighting arrangement is useful for observing the convection currents of air. However, the refractive power of air is much less than that of water, and an equally effective demonstration of changes in the refractive index requires a more efficient and more expensive optical system, such as the one currently used in studying aerodynamic problems. It is possible to detect the existence of convection currents in a room by cutting a thin sheet of paper in a spiral (Illustration 2a) and supporting it on a pinpoint (Illustration 2b). Even rather slow vertical movements of air will cause the spiral to rotate rapidly. Two convenient sources of convection currents in a room would be a radiator or a light bulb. The warm air generally rises at a speed of an inch or a few inches per second, depending on the temperature of the surface of the radiator or the glass of the illuminated bulb and the overall room temperature.

line, therefore, but will be turned from its path as it encounters water of different temperature. These striations can be made even more apparent by illuminating the beaker with a concentrated beam of light (such as that from a pocket flashlight focused through a lens). If the convective currents are observed from a position behind the beam of light, they can be seen quite clearly.



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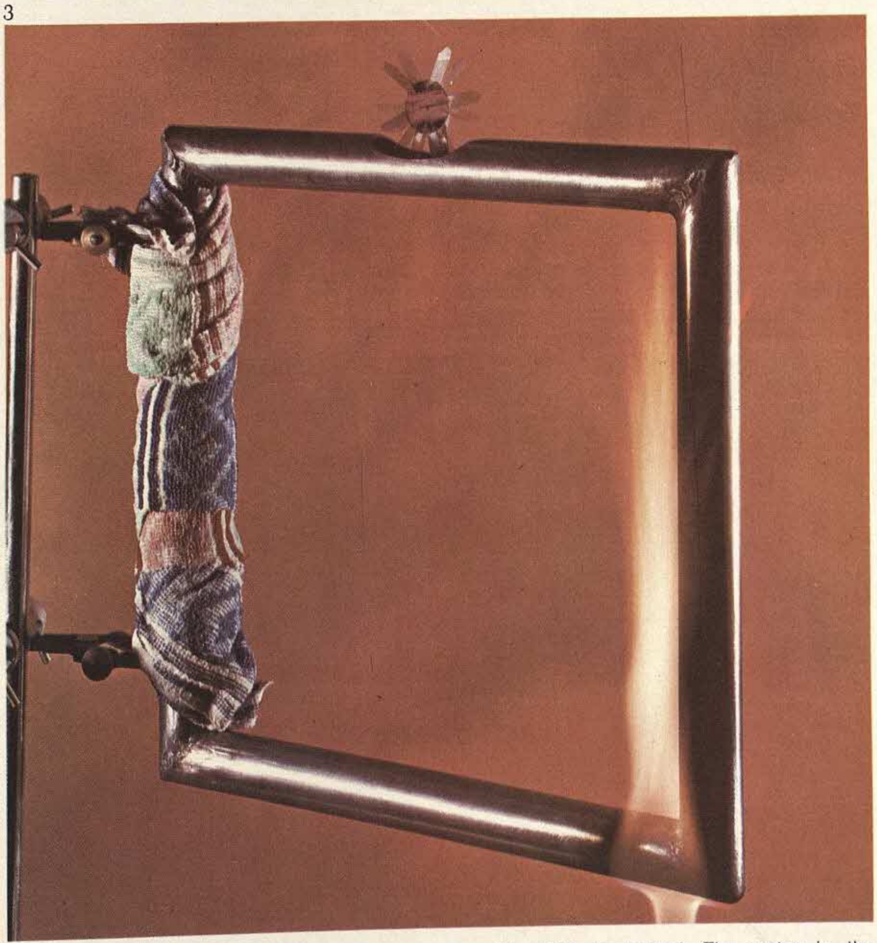
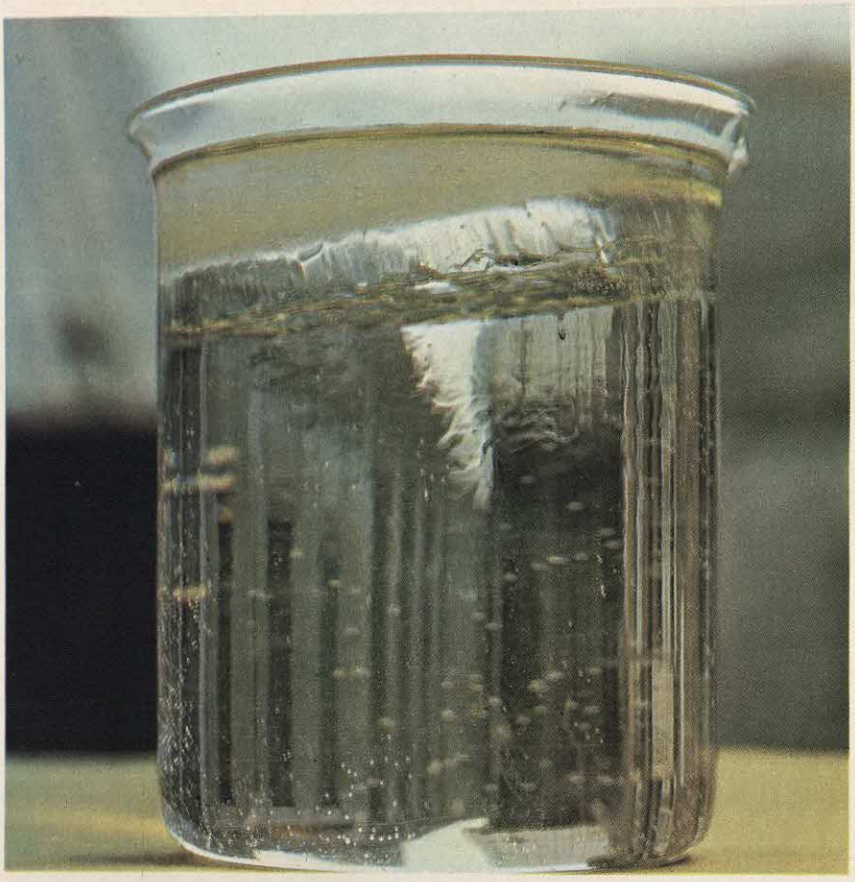


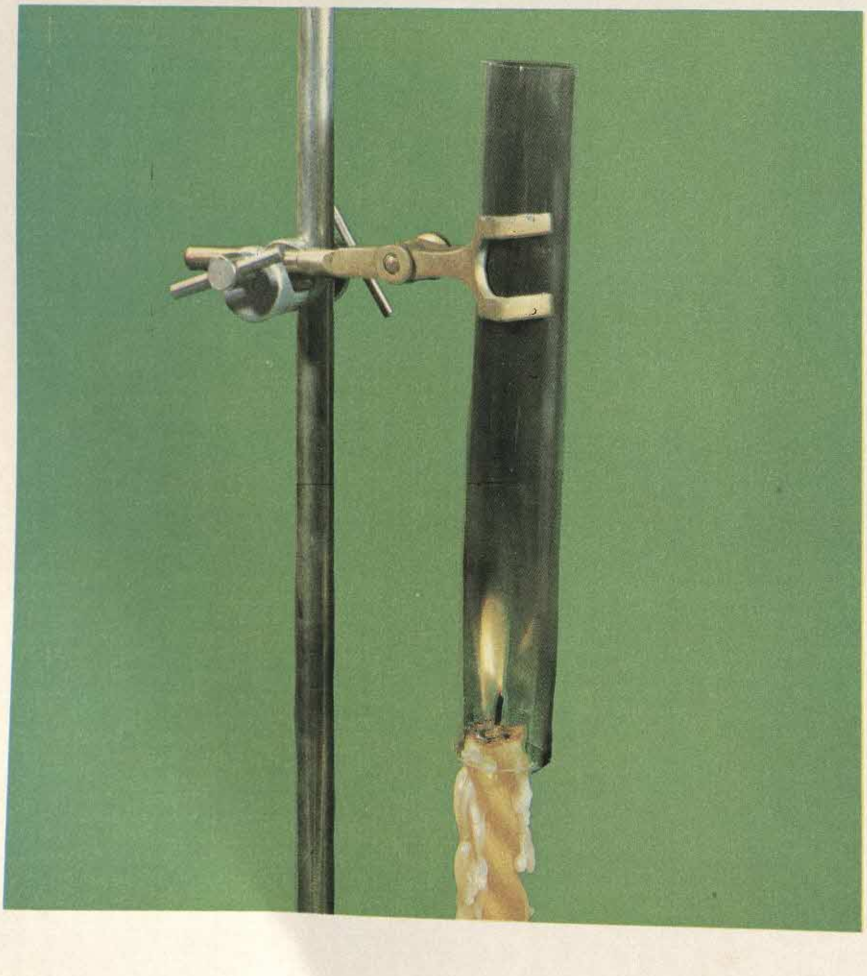
A CONVECTION MOTOR—A simple construction will demonstrate how continuous circulation of water can be produced, and how this circulation could theoretically be used to supply mechanical power to a paddle wheel. Four lengths of piping are welded, as shown in this photograph, to form a square with an opening at the top; the pipes are then filled with water. One of the vertical sides is cooled by wrapping a wet rag around it; at the same time, the opposite side is heated. The water in the heated side will rise and descend on the cooled side. This movement is sufficient to rotate a light paddle wheel, shown at the top of the construction. A central heating system is based on somewhat the same system: the water is heated in the boiler, rises along the pipes, passes through the radiators, rises to the top of the building, and then—having lost most of its heat—returns to the boiler.



4

CONVECTION CURRENT PRODUCED BY A COLD SOURCE—If a cold object is immersed in water, the cooled water will fall to the bottom of the container. To illustrate this principle, some water is poured into a container similar to that in Illustration 1, stirred until its temperature is uniform, and allowed to rest until it is perfectly still. Then a small piece of ice is held by a pair of tongs just below the surface. As the top layer of water is cooled, a flow will occur downward and there will appear descending from the ice what looks like threads of water, caused by the greater refractive power of the cooled particles of water. If it is assumed that the temperature of the water in the container is 20° C (68° F) and that of the water in direct contact with the ice is 2° C (35.6° F), the density of the cooled water is approximately 0.2 percent greater than that of the surrounding water. In other words, a cubic centimeter of water at 2° C weighs as much as 2 mg more than a cubic centimeter of water at 20° C; therefore, it will fall to the bottom of the container.

5



DRAFT—Flames are also examples of convection currents; they are composed of gases much hotter than air, which therefore rise above the surrounding air. Because the gases are luminous, they can clearly be seen as they rise within the flame; they do not stop rising when they reach the point of the flame, but merely become colorless and less visible unless the flame is smoky (such as the flame of a candle), in which they appear as a smoky trail rising from the tip of the flame. In order to keep the flame in combustion, considerable air is required; in furnaces and burners it is sometimes necessary to produce this flow of air by using a pump. This represents an expenditure of energy that may be supplied, in some cases, by exploiting the energy of the hot gases themselves. If a flame is made to burn at the base of a vertical tube, for example, its hot gases will mix with the air within the tube and cause it to rise, thus drawing a supply of air toward the base of the tube that will feed the flame. The photograph shows a glass tube with a diameter of about 25 mm (about 1 in.) held above the flame of a candle; the flame burning at the end of the tube heats the air contained in it and makes it lighter. The upthrust provided by the air at room temperature draws the lighter air upward. It is possible to calculate the acceleration of this upward movement. If the flame heats the tube to a temperature of about 300° C (572° F), inasmuch as the density of air diminishes in inverse proportion to the absolute temperature, the density of the air inside the tube will be about half that of normal air—for 300° C is a temperature 600° C above absolute zero. The temperature of the air is, therefore, approximately doubled; thus the density is halved. Each cubic centimeter of air inside the tube will be subject to an upthrust equal to about half its weight and, consequently, will be accelerated vertically.

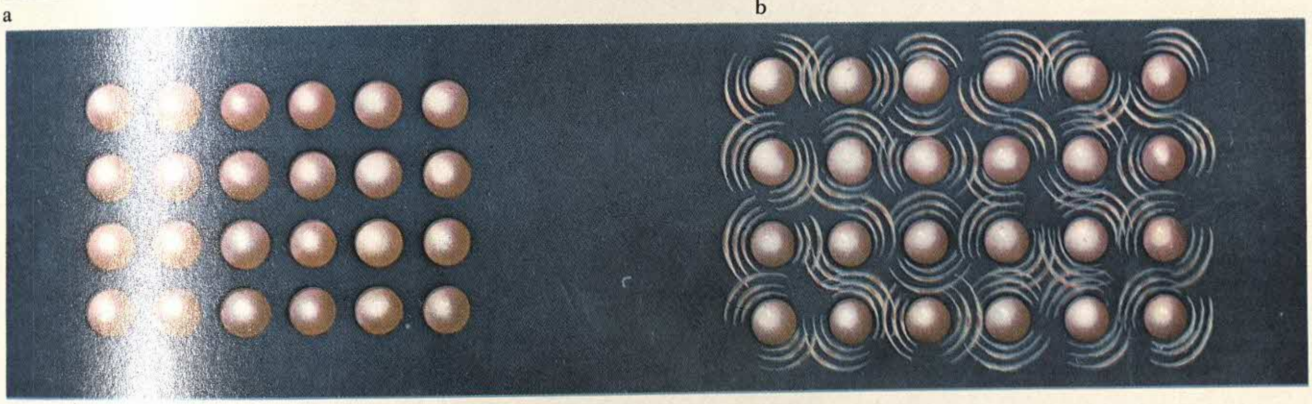
HEAT EXPANSION | a vital factor in architecture and engineering

In the field of architecture, the comment is sometimes made that each building has a life of its own; that it is created in the image and likeness of a concept in the mind of an architect; and that when it is used, it takes on a function and lifestyle all its own, much like a human being. Physics can add this detail to the description: buildings "breathe"; they expand in heat and contract in cold.

When the temperature of a solid body is raised as little as one degree, its length increases about a hundred-thousandth part of its original value. This may seem negligible, yet it must be taken into account in building and machinery construction.

Railroads, bridges, buildings, water pipes, engines—all must be designed and constructed in such a way that their various parts will be permitted to expand when subjected to temperature increases and to contract when they are subjected to drops in temperature. The task here is twofold: (1) to study the property of solid bodies whereby they change their dimensions as temperature varies; and (2) to relate this phenomenon to the crystalline structure of the bodies.

1



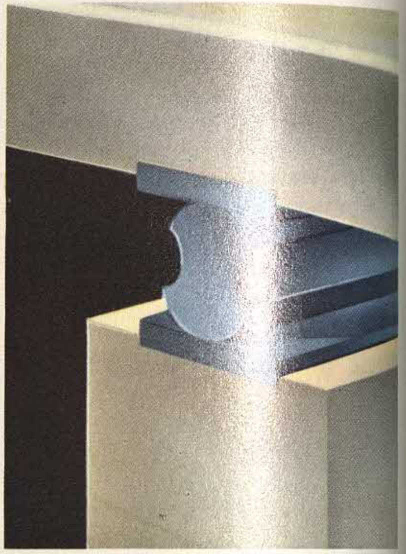
A PIECE OF COLD METAL ENLARGED A HUNDRED MILLION TIMES—In Illustration 1a, the small spheres represent atoms distributed in a metallic crystal. The atoms are arranged in a lattice with a square mesh; they can be considered as being practically in fixed positions. Illustration 1b shows the same metal after it has been brought to a much higher temperature (several hundred degrees). The atoms are still at the nodes of the square-mesh lattice, but they now vibrate very strongly around their equilibrium position. This vibration is practically negligible at a low temperature, but at high temperatures it becomes much more pronounced and the distance between the atoms increases. The metallic body thus becomes larger.

2

LINEAR EXPANSION AND VOLUME EXPANSION—A body undergoes a variation in volume every time its temperature is raised: the cube of brass shown here first occupies a certain volume **a,** but after it has been heated, it occupies a greater volume **b.** This phenomenon is called thermal expansion. When a small section of a bar is subjected to an increase of temperature, the volume of the bar increases; how much it elongates becomes a problem in linear expansion. When volume variations are involved, the problem becomes one of volume expansion. The elongation is here defined as the difference $l' - l$ in the length of the bar before l and after l' it is heated. How will the elongation of the bar vary in terms of the temperature variation and the original length of the bar? The elongation will be great if a very long bar is heated by one degree, but it will be small if the temperature of a short bar is raised by the same amount. Thus, the elongation is directly proportional to the original length of the bar. Moreover, the more the bar is heated, the greater will be the elongation.

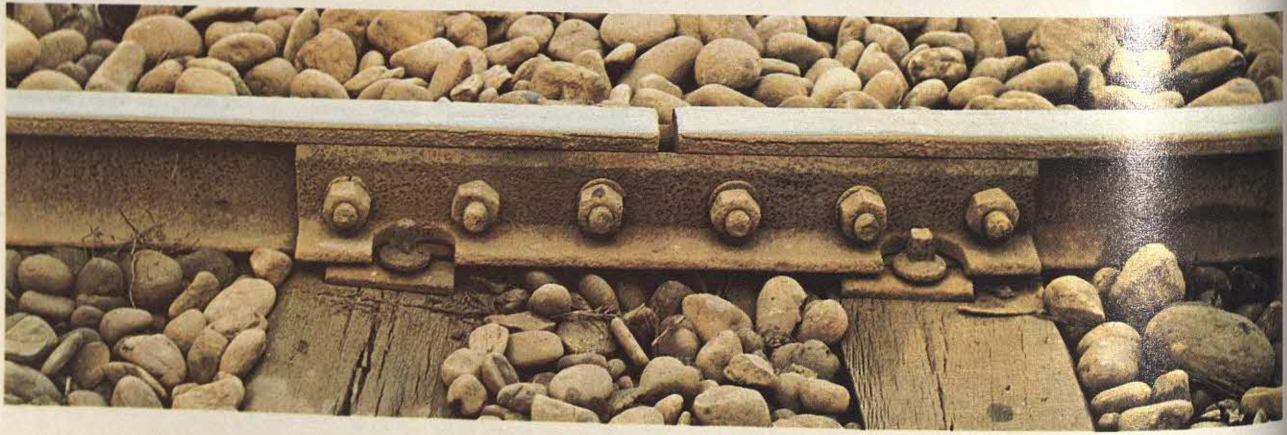
The expansion $l' - l$ of a body when its temperature is raised one degree, divided by the original length l of the body, is the coefficient of thermal expansion. For example, the coefficient of thermal expansion of iron is approximately 0.00001. This means a piece of iron will elongate by a hundred-thousandth part of its length every time its temperature is increased by one degree.

3



BRIDGE EXPANSION—The body of a bridge, since it is suspended in air, is subject to the temperature variations of this air. It will therefore expand about 1 mm (about 0.04 in.) for every 10 m (about 33 ft) of its length every time the temperature increases 10°, and it could easily fracture at some point if it were not constructed in such a way as to permit these variations of length. One way to permit a bridge to expand or contract as it reacts to temperature variations is to support one end of it on a pier with a steel roller. Since the bridge is interrupted on one side of this support, only a small rotation of the roller occurs whenever the bridge expands or contracts.

4



RAILS NEED EXPANSION JOINTS—If an iron bar (original length $l = 20$ cm) is heated by 11 C°, its length will increase until it reaches a value $l' = 20.00242$ cm. It, therefore, expands by

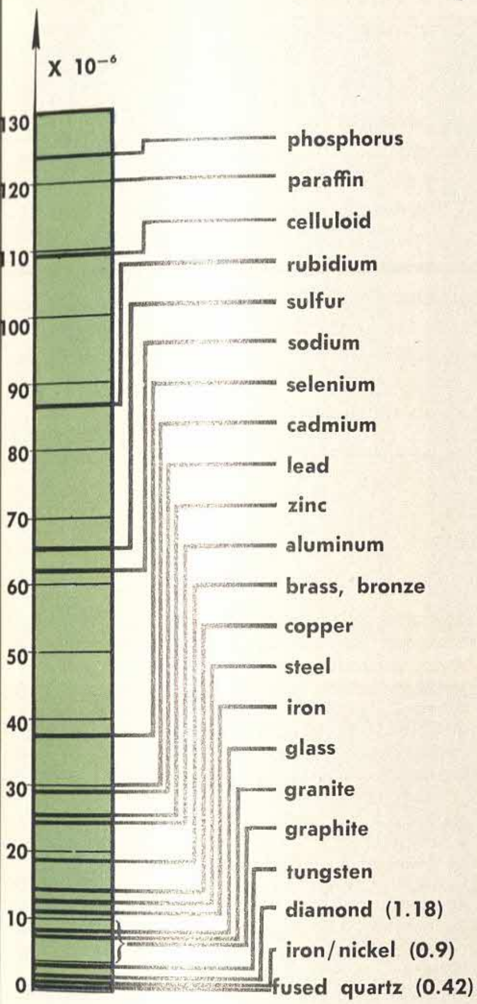
$$\frac{l'-l}{l} = \frac{20.00242 - 20}{20} = \frac{0.00242}{20} = 0.000121$$

of its length every 11 C°. The expansion for one degree will be

$$\frac{0.000121}{11} = 0.000011;$$

in other words, the coefficient of expansion is eleven millionths of a centimeter per centimeter per degree. The rails therefore must be joined in such a way that a small space is left between them; this permits the expansion caused by the increase in temperature during a hot summer. A rail 20 m long whose temperature is raised by 40° (the temperature variation that rails undergo between winter and summer) elongates in the following way: when the temperature rises one degree, the elongation amounts to 0.00001 of 20 m; that is, 0.2 mm. When the temperature rises 40°, the elongation will be 40 times as great; that is, 8 mm.

5



DIFFERENCES IN EXPANSION—This illustration shows how much various substances expand when their temperature is rasied one degree. For example, celluloid, one of the solid substances that expand most, elongates by 110 millionths of its length for every increase of one degree in its temperature. In other words, when a piece of celluloid 10 cm long is heated so that its temperature increases only one degree, it will increase by 110 millionths (about 0.0001) of its length, or 0.01 mm.

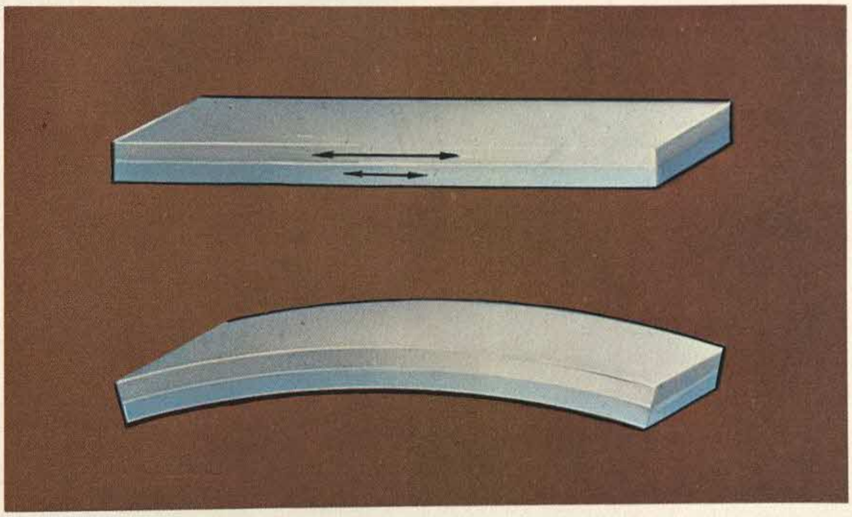
Some substances, like phosphorus and paraffin, expand more than celluloid, but most of them expand much less. The substance that expands least of all is fused quartz. If a crystal of quartz is fused and then cooled very rapidly, the liquid will set and become hard without crystallizing: the result is silica glass or fused quartz. This noncrystalline quartz, the so-called amorphous quartz (because its atoms are arranged at random), has the smallest known coefficient of expansion.

A bar of fused quartz 10 cm long will lengthen by about 0.00005 mm. This is about 200 times less than the piece of celluloid considered above. The limited expansion capability of fused quartz is exploited in the construction of instruments that call for parts little affected by temperature variations.

The diamond is another substance that does not expand much. Actually, it expands only slightly more than twice as much as fused quartz.

Cement expands about as much as steel. Among the metals, tungsten has one of the smallest coefficients of thermal expansion.

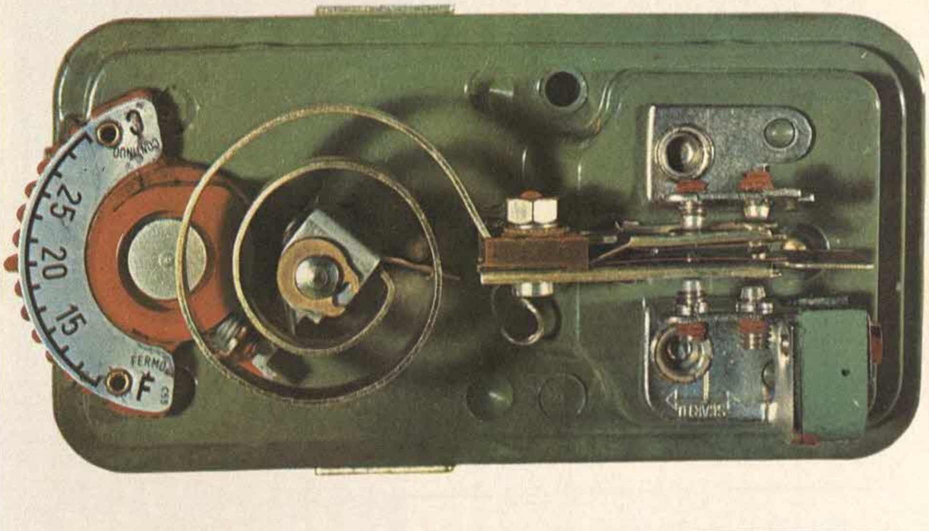
6



DIFFERENT RATES OF EXPANSION—Two thin sheets of metal have been welded against one another. Since the metals are not similar, they expand differently when heated. One expands more than the other. The one that expands more will tend to elongate the bar as the temperature rises; the one that expands less will oppose the elongation. An increase in temperature will cause the bar to bend: the metal that has elongated more will come to lie on the longer, outer circumferential arc, while the metal that has elongated less will come to lie on the shorter, inside face of the arc. Such laminated pairs are usually called bimetals.

7

TEMPERATURE MEASUREMENT—If a strip of bimetal is bent to form a spiral, the expansion of the strip will cause the spiral to curl and uncurl according to the temperature. This action can be used to indicate the temperature.



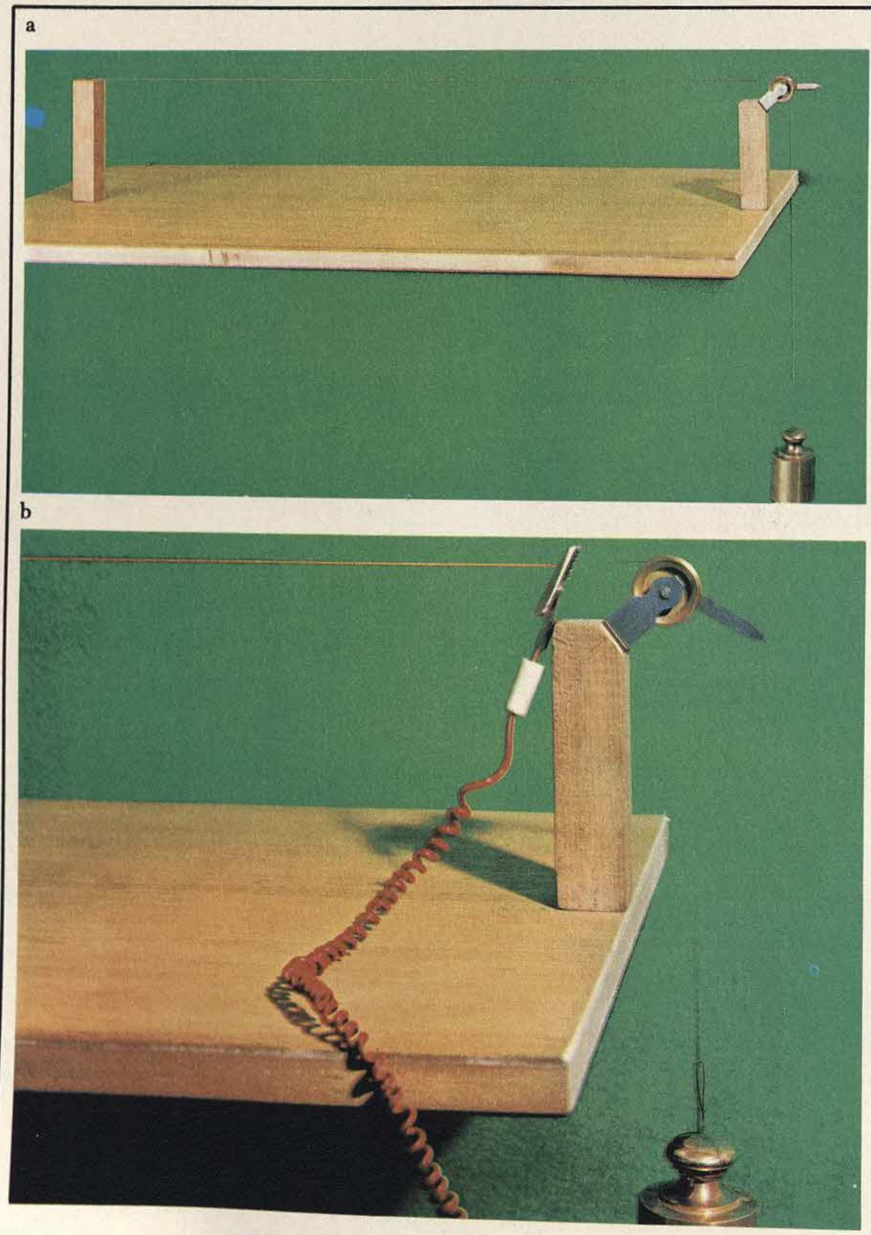
THERMAL EXPANSION | the relationship of volume and temperature

Matter consists of atoms and molecules that are not motionless, but are rather in a state of continuous agitation, moving freely at a certain distance from one another. If this agitation is increased, as it is when temperature increases, the space between them also increases (with rare exceptions), and the dimensions of the body consisting of these atoms and molecules also increase. In other words, almost all bodies expand and increase in volume as their temperature rises; this characteristic is known as thermal expansion.

The amount of increase depends on various factors. Gases expand most of all, liquids somewhat less, and solids least.

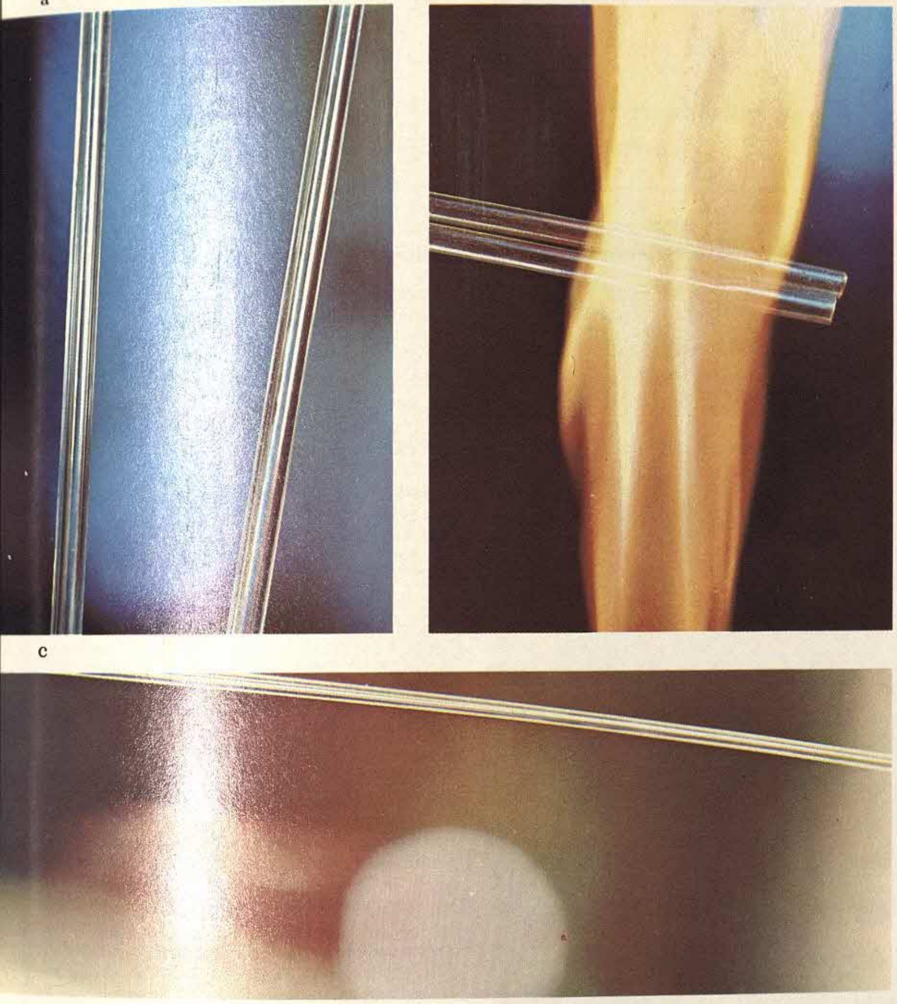
A number of experiments make it possible to ascertain the quantitative variation in the dimensions of bodies subjected to heating or cooling. In some cases, this variation is difficult to observe; for example, if the temperature of a steel rod 10 cm (about 4 in.) long is increased by 10 C° (about 18 F°), its length will increase by no more than 0.01 mm (about 0.0004 in.); such a small difference is difficult to measure without delicate and expensive instruments. It is possible, however, to construct experimental equipment that is both simple and suitable for disclosing minute variations in the dimensions of certain bodies resulting from changes in their temperatures.

1



THE EXPANSION OF STEEL—This experiment does not disclose the precise coefficient of linear expansion of steel—the change in the length of a specific unit for 1 C° change in temperature—but it does demonstrate that steel expands, and it also provides an approximation of the coefficient of expansion. The equipment includes: a wooden board about 120 cm (about 4 ft) long, just under 0.5 m (about 20 in.) wide, and preferably at least 3 cm (about 1 in.) thick; two wooden pegs to be glued on the board very rigidly, as shown in the illustration; a length of steel wire (such as a guitar string) with a diameter of about 0.3 mm (about 0.012 in.); a small pulley wheel; a weight of about 1 kg (2 lb); and a storage battery. The wire is fixed to the peg on the left side of the board and stretched to the pulley wheel that is attached to the right-hand peg and equipped with a movable pointer. The wire is wound twice around the wheel; the pointer is then set in a horizontal position and held there as the wire is held taut by the weight at its end (Illustration 1a). The wire is heated by connecting its ends to the battery and passing a strong current through the wire. This current should be regulated by a resistance unit in the circuit. When the wire becomes red-hot (Illustration 1b), its temperature will be about 500° C (932° F); the wire will have expanded and the weight will have pulled it taut so that the pointer on the pulley wheel will have moved from a horizontal position to an angle. The hotter the wire, the more it expands, and the greater the angle of the pointer.

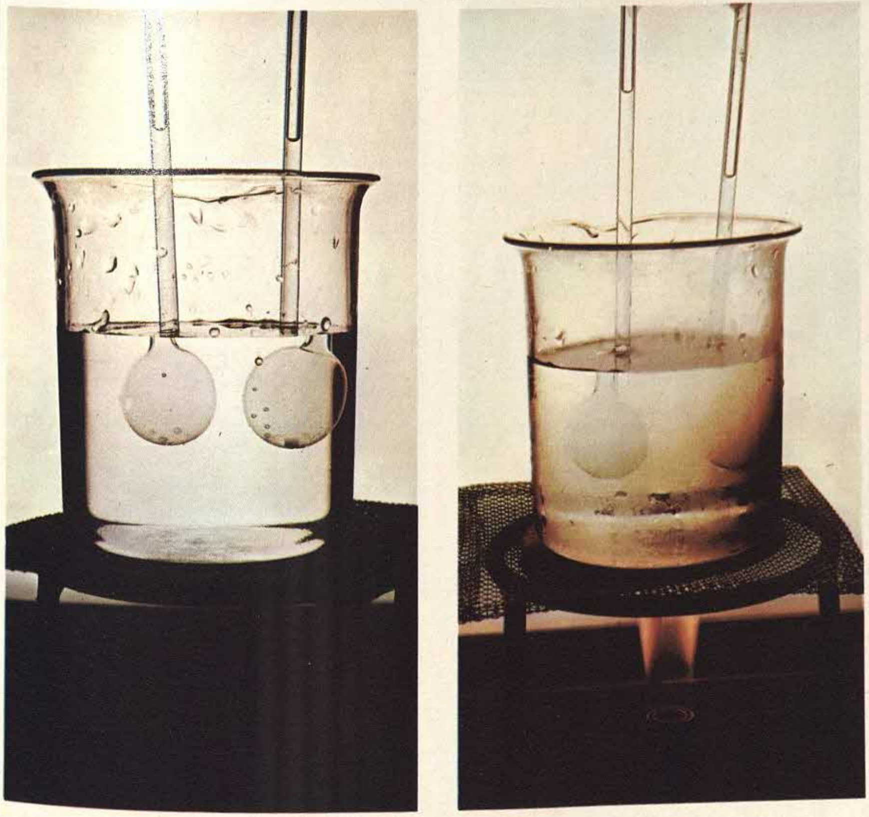
A wire 1 m (about 39 in.) in length, heated to about 500° C (932° F), will expand about 5 mm (about 0.2 in.), an appreciable length. Even if the wire is only heated to about 100° C (212° F), it will expand enough to move the pointer.



2

THE EXPANSION OF GLASS—The coefficient of expansion of glass cannot be measured by heating glass electrically, because glass does not conduct electricity. Glass can be heated by contact with a hot body; however, another interesting experiment will demonstrate the difference between the expansion coefficients of two different types of glass. This is not as difficult as it might seem, even though the coefficients are very similar (unless glass of very special composition is used); nor is it necessary to find the difference by extremely accurate measurements of each coefficient. All that is required are rods of two types of glass (Illustration 2a), a burner, and tongs. Each of the rods should be drawn by heating over the flame to a diameter of 1 mm (about 0.04 in.), and broken into lengths of about 3 cm (about 1.2 in.). After the rods have cooled, they are picked up with the tongs and held in close contact with one another over the flame (Illustration 2b); they will soon soften and join, but without mixing. As soon as they have joined, they should be drawn still further until their joined diameter is reduced to about 0.1 mm (about 0.004 in.), then left to cool. As soon as the temperature falls, the glass fiber will begin to curve (Illustration 2c), because the fiber is composed of glass with two different coefficients of expansion. Once the glass has hardened, the two types of glass will have contracted by different amounts—that is, the glass with the greater coefficient of expansion will have become shorter than the other, and the fiber will have become concave on the side formed by this glass. This method is used to ascertain whether two types of glass can be joined. If the two coefficients of expansion differ too greatly, it is still possible to join them; when they have cooled, however, the contraction will cause the joined section to fracture.

3



THE EXPANSION OF LIQUIDS—The molecules of liquids are not quite so cohesive as those of solids, and they are not held in rigid positions in relation to one another as are those of solids; therefore, when temperature is increased and these molecules are more agitated, they readily move farther apart. This results in a greater capacity to expand under heat than the molecules of solids. The expansion of a liquid is, therefore, more easily observed than that of a solid.

To make such an observation, the experimenter needs two capillary tubes with bulbs at the end, similar to those of a thermometer, and a beaker of water. The two tubes are placed in the beaker and each tube receives enough of a different liquid to reach the same level in the capillary section just above the bulb, as shown in Illustration 3a. The two liquids are pure alcohol and pure water, which have different coefficients of expansion. (These coefficients are not linear, as in the case of the solids previously mentioned, but coefficients of volume expansion—the change in the volume of a specific unit for 1 C° change in temperature.) The known coefficient for alcohol is 0.112; that for pure water is only 0.0207. By increasing the temperature of the water in the beaker that holds the two partly filled tubes, it is easily observed that the alcohol in the tube on the left will rise in the capillary to a higher level than the water in the tube on the right (Illustration 3b).

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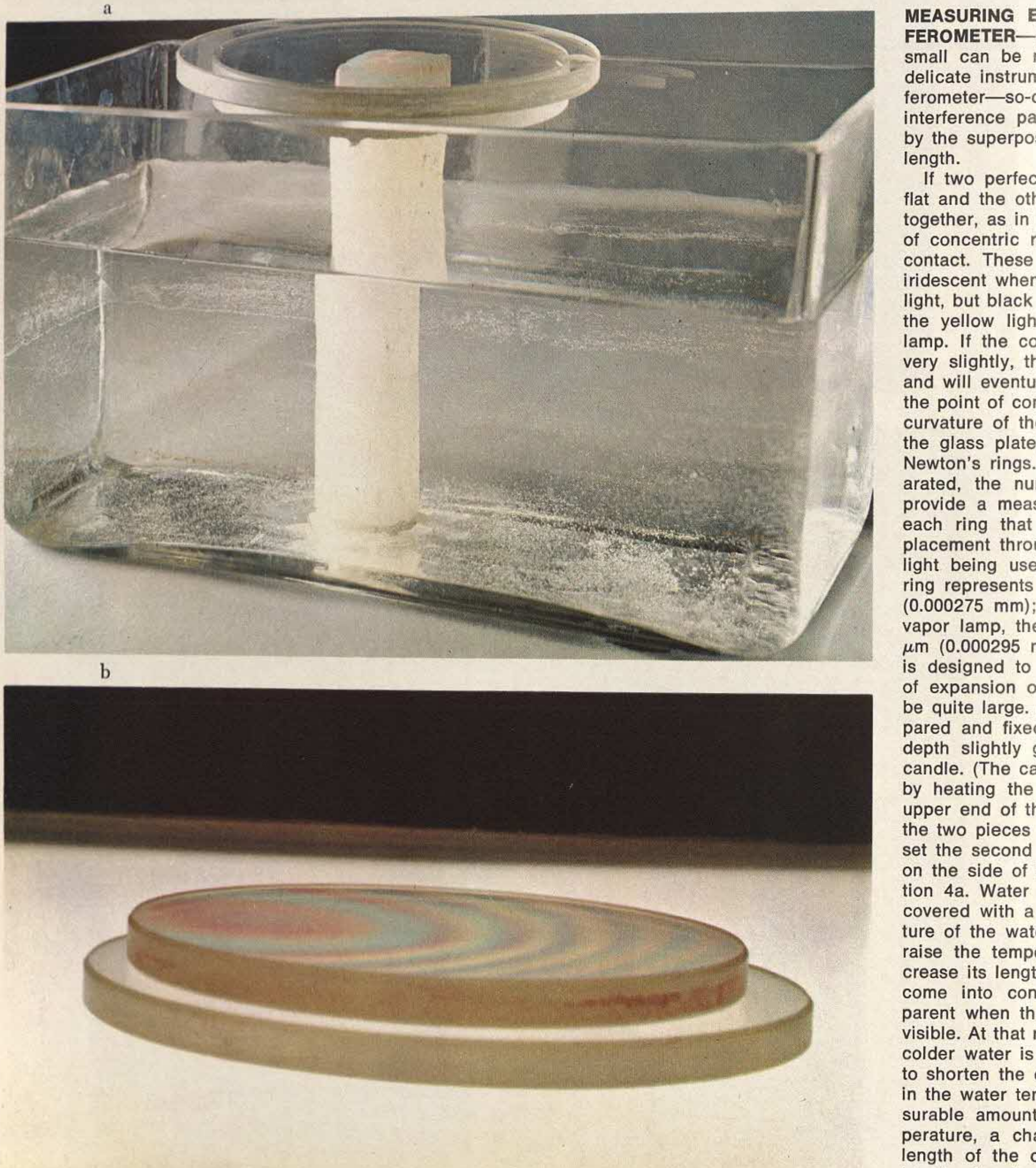


MEASURING EXPANSION WITH AN INTERFEROMETER—Expansions that are extremely small can be measured by one of the most delicate instruments used in optics, the interferometer—so-called because it produces an interference pattern of rings of light caused by the superposition of light waves of varying length.

If two perfectly clean pieces of glass, one flat and the other slightly convex, are placed together, as in Illustration 4b, a large number of concentric rings will form at the point of contact. These so-called Newton's rings are iridescent when they are illuminated by white light, but black and white when illuminated by the yellow light emitted by a sodium vapor lamp. If the convex piece, or lens, is raised very slightly, the rings will become narrower and will eventually disappear in the center at the point of contact. The greater the radius of curvature of the lens surface in contact with the glass plate, the more visible will be the Newton's rings. As the two surfaces are separated, the number of rings that disappear provide a measurement of the displacement; each ring that disappears represents a displacement through half the wavelength of the light being used. If this is white light, each ring represents a distance of about 0.275 μm (0.000275 mm); if it is the light of a sodium vapor lamp, the distance will be about 0.295 μm (0.000295 mm). The following experiment is designed to obtain the precise coefficient of expansion of paraffin, which is known to be quite large. A small paraffin candle is prepared and fixed upright in a glass tank of a depth slightly greater than the length of the candle. (The candle can be fixed to the glass by heating the base of the candle.) On the upper end of the candle is set the smaller of the two pieces of glass, and on top of this is set the second piece of glass so that it rests on the side of the tank, as shown in Illustration 4a. Water is placed in the tank, and is covered with a thin film of oil. The temperature of the water is raised slowly in order to raise the temperature of the candle and increase its length until the two pieces of glass come into contact—which will become apparent when the Newton's rings first become visible. At that moment the experiment begins: colder water is poured into the tank in order to shorten the candle; even a slight decrease in the water temperature will result in a measurable amount of shortening. At room temperature, a change of 1 C° will cause the length of the candle to change 0.001 of its length; therefore, if enough water is added to drop the temperature by 1 C°, a candle 10 cm (about 4 in.) long will be shortened by 0.1 mm (about 0.004 in.). The variations in the length of the candle can be observed by the movements of the rings of the interferometer, even if they are of the order of as little as 1/1000 C°—a change that can be obtained by the addition of just a few drops of water.

THE RADIATION OF HEAT

thermal energy passing through space

Heat can be transferred from one body to another in several ways. When it is transferred by conduction, the added agitation of the molecules that produces the phenomenon of heat passes from molecule to molecule by direct contact; the molecules do not leave their position in the body, but pass the energy within the body. This form of heat transfer is, therefore, appropriate to solids. When heat is transferred by convection, a form of transfer characteristic of fluids, the added agitation of the molecules causes them to abandon their original positions and move away from one another—to expand; the entire body moves in space, carrying the heat with it. When heat is transferred by radiation, however, no movement of the agitated molecules or of the body is involved; radiant heat can pass through a vacuum and also through objects that are transparent to visible light. Radiant heat is composed of electromagnetic waves, similar to those of light and moving with the speed of light; its waves, however, are longer than light waves.

All bodies radiate heat energy, no matter how cold they may seem; but the more agitated the molecules of a body, the more heat waves are radiated, according to a proportion that can be measured. Similarly, all bodies absorb heat energy, but at different rates. Simple experiments illustrate the more important characteristics of radiant heat.

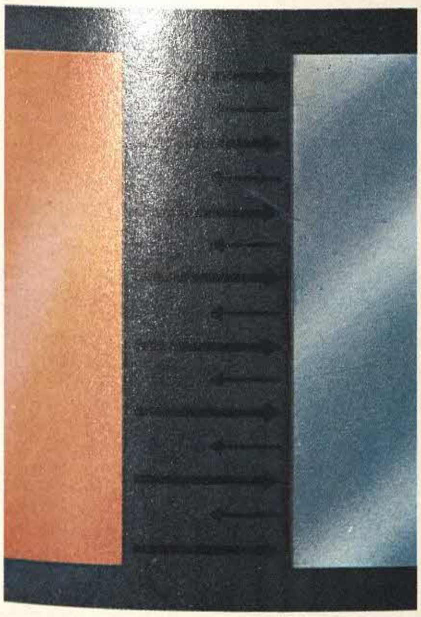
TWO-WAY RADIATION—Radiation consists of the transmission of energy, in the form of electromagnetic waves, between material bodies. When heat energy is transmitted by electromagnetic waves, the radiation takes place between all bodies, but the radiation from a cold body toward a hot body is slower than that of a hot body toward a cold body. Consequently, the net effect of an exchange of energy between the two bodies is an excess of radiation in the direction of the hot body from the cold body, and in practice it appears that this is the sole direction. In other words, radiant heat appears to travel only from a hot to a cold body.

The yellow rectangle in Illustration 1a represents a hot body, the gray diagram a cold body; in the space between them are arrows representing electromagnetic waves. The strong emission from the hot body toward the cold body is indicated by long arrows; the weak emission in the opposite direction is indicated by short arrows. It must be emphasized that these arrows represent the heat of radiation only, not that of convection or conduction. (The different modes of transference are subject to different laws.)

The experiment that will illustrate these principles (Illustration 1b) requires a sheet of glass or, even better, transparent plastic, no more than 1 mm (0.039 in.) thick, mounted in a small wooden frame about 20 cm × 30 cm (about 8 in. by 12 in.) in size, and an electric iron. The frame is placed vertically in the center of a table. When the iron is heated, the glass or plastic acts as a barrier to heat by convection. Nevertheless, if a hand is placed so that the glass or plastic is between it and the iron, considerable heat will still be felt—as much as 150° C (302° F). Inasmuch as no heat could have been carried by convection and, obviously, none could be carried by conduction (the hand was not in contact with the iron), it must have been transmitted by radiation.

The same effect will be obtained, in reverse, by a similar arrangement (Illustration 1c), in which the heated electric iron, a body hotter than the hand, is replaced by a block of ice, a body colder than the hand. (Two trays of ice may be used in place of the block ice, if necessary.) Both the ice and the hand must be placed closer to the frame than in the previous experiment. The hand will become much colder on the side held toward the ice than on the other side, even though the amount of radiation—in this case from the hand toward the ice—is only of the order of 30° C (86° F), far less than that of the previous experiment. The transmission of heat from hand to ice, however, which is felt as a sensation of cold, is nevertheless an example of heat radiation.

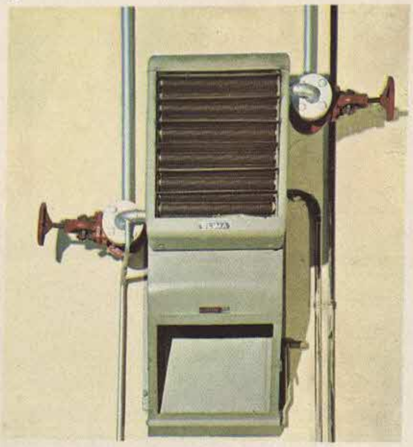
1a



1b

1c

2

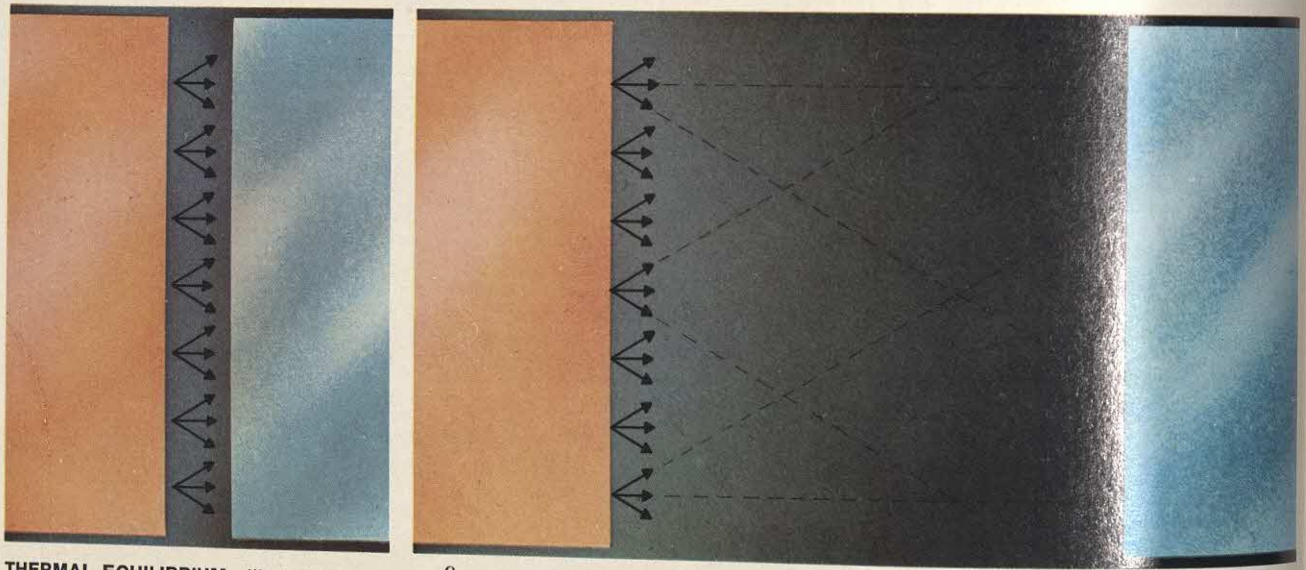


RADIATION BALANCES CONVECTION—In the environment in which man lives, he must be sure that he is supplied with heat, both by convection and by radiation, from walls that have the same temperature as the air. A room with a high air temperature may seem warm; yet, if the walls are cold, the body will radiate heat toward them and will become too cool. That is why it is possible to catch cold because of poor heating arrangements. If a window is opened on a cold day and then closed after the air in the room has become cool, the walls may still be warm; this will unbalance the body's thermal regulation. On the other hand, in a room with cold walls—such as a church or a warehouse at the end of winter—a similar imbalance may develop once the warm air has begun to enter from outside, or the internal heating system has been placed in operation. The illustration shows a heating apparatus used to warm the air of a large industrial area; it may well heat the air inside but leave the walls almost as cold as they were initially.

3

a

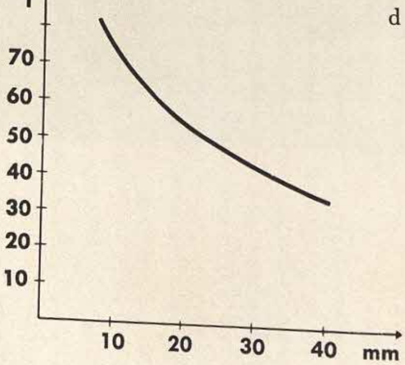
b



THERMAL EQUILIBRIUM—Illustrations 3a and 3b each show two bodies, one hot and the other cold. In Illustration 3a, the bodies are shown without much space between them. The body on the left is assumed to be quite large and very hot—say, 1,500° C (2,732° F); the body on the right is assumed to be a thin layer of cold conducting material placed in contact with an object of high insulating capacity. As soon as the two bodies are brought close together, the body on the left will radiate heat toward the body on the right, raising its temperature. (This increase in heat in the body on the right cannot be the result of conduction, because the body is backed up by insulating material.) If the two bodies were left near each other for a considerable period of time, the continued radiation would cause the body on the right to gain heat at the expense of the body on the left. Eventually, the two bodies would have the same temperature, thus producing a thermal equilibrium that could easily be detected by a thermometer.

In Illustration 3b, the same two bodies are shown farther apart. It is assumed that the radiation of heat from left to right occurs at the same rate; but because of the space between the bodies, the body on the right would receive less radiation than in the first case. Moreover, it can give up to the intervening space part of the heat it receives, and its temperature will not reach a level as high as in the previous case.

c



The same phenomenon can be illustrated in another way, by exposing an ordinary thermometer, capable of recording high temperatures, to the sun's rays. First it should be exposed with an opaque screen between the rays and the bulb, and this temperature, which is the temperature of the surrounding air, should be recorded. Then the screen should be removed and the rays should be allowed to hit the bulb directly; this will cause the temperature to rise. Next, a large magnifying glass should be placed between the rays and the bulb in such a position that it will not concentrate the rays on the bulb, as shown in the photograph. The glass can be held very close to the bulb at first, then gradually moved away until the bulb is at the focus of the lens. As the rays are concentrated on the bulb, the temperature will continue to rise. (Care must be taken lest the thermometer break because of the intensity of the heat.)

Illustration 3d is a graph showing the difference in temperature of the bulb and the surrounding air, plotted against the increasing diameter of the out-of-focus image of the sun. If the experiment is continued, it is necessary to use metals, which have a higher melting point than glass.

MORE ABSORPTION, MORE RADIATION—An interesting experiment can be carried out by confirming that the temperature registered by the thermometer in the previous experiment would be increased by blackening the bulb (applying a coat of opaque black paint, for example). If the temperature of the clear bulb registered 50° C (122° F), that of the blackened bulb would register 55° C (131° F). The blackening not only increases the absorptive capacity of an object; it also increases its emission capacity. This can be demonstrated by blackening the surface of the iron in the experiment in Illustration 1, and then repeating the experiment. The hand will warm up even more quickly than before, because the iron has acquired the characteristics of a typical black body.

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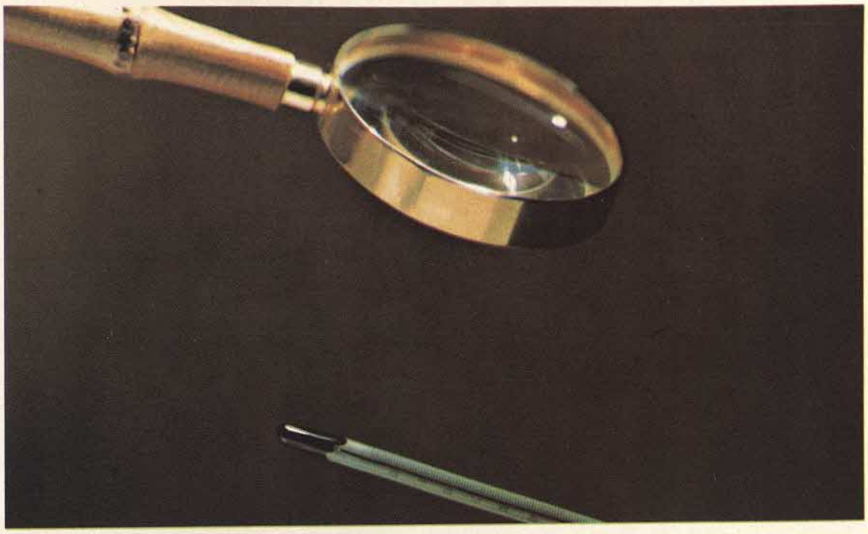

TWO LAWS OF RADIATION—Two important laws concern the intensity of radiation emitted at various temperatures and the spectral composition of radiation.

According to the first law, the amount of radiation increases in proportion to the absolute temperature carried to the fourth power. The energy radiated at two different temperatures, 1,027° C and 2,327° C (1,880.6° F and 4,220° F), illustrates the law. First, these temperatures must be converted to their equivalents on the Kelvin (absolute) scale; when that is done, the second temperature is exactly twice that of the first. Now, 2 to the fourth power (2^4) is 16; therefore, the amount of energy radiated at 2,327° C is 16 times the amount radiated at 1,027° C.

According to the second law, an increase in temperature causes the absorption spectrum of the radiation to favor the blue and violet colors. In practice, radiation emitted by bodies at temperatures only slightly above 550° C (1,022° F) is predominantly red (at the long end of the spectrum, farthest from violet), and becomes progressively yellow, white, and bluish-white as the temperature increases.

It can be demonstrated that a hot body emits heat energy very rapidly at high temperatures and more slowly at lower temperatures; a body will tend to cool very rapidly at first, then more slowly. The rate of cooling of a body that loses its energy predominantly through radiation can be measured by the cooling rate of an electric light bulb filament, as shown in the photographs of an experiment carried out with a motion picture camera (preferably an 8-mm camera, which is easily focused for short distances). The camera is aimed at the bulb of a slide projector. The lens of the projector at first shows a light so dazzling that the pictures will be superposed and will not show anything. As the film is rolled, the projector light is turned off; successive frames of the film are shown, proving the progressive diminution of the light emitted by the filament, which, lacking electrical energy, will gradually cool, losing its energy by radiation. It can be seen that the filament reddens very rapidly when the electricity is turned off. The intensity of the radiation falls off very rapidly at first, when the filament is still hot, having fallen from the 2,350° C (4,262° F) of the fully lighted bulb to about 2,000° C (3,632° F). As the radiation is reduced, the temperature falls more slowly. The red color covers more of the length of film than any other color.

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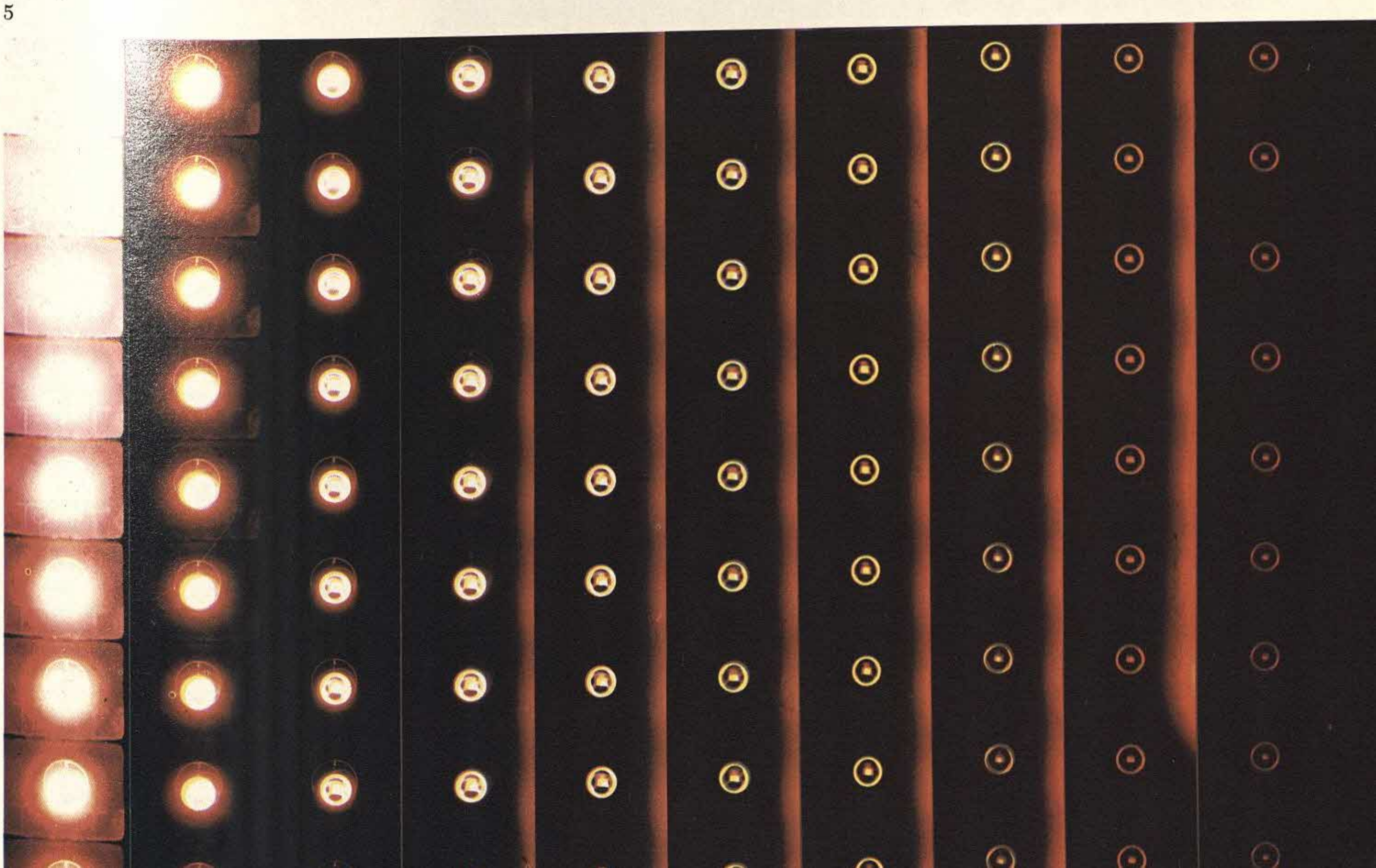

THERMODYNAMIC MAGNITUDES

relationships between heat and work

Matter seems, on the basis of observation made during many experiments, to be continuous; but it is actually composed of many separate particles—molecules and atoms and elementary particles. The properties of matter depend, in the last analysis, on the properties of these particles, a knowledge of which could theoretically make it possible to calculate the properties of matter in its macroscopic (that is, tangible or visible) aspects. It is not always possible, however, to know all the properties of the component particles, and it is often more convenient to deduce these properties from a study of macroscopic matter. The existence of the molecules of a gas, for example, can be demonstrated by studying the properties of the gas in phenomena that can be observed when the gas is liquefied.

The microscopic properties of matter—that is, the properties of the component atoms and molecules—can be observed more readily when a substance is in its gaseous phase, because in this phase (or state) its molecules are very widely separated and interact so infrequently that they can be considered, for practical or experimental purposes, entirely free. When a substance is in its solid or liquid phase, on the other hand, its atoms and molecules are so close together that they exert mutual forces that modify their structures and modify the real nature of the phenomena.

Even though the gases are particularly interesting to study, it must be remembered that despite their relative lack of density, the smallest volume of gas contains a vast number of atoms—and it is not possible to follow the movement of each atom. For that reason, even a gas is most conveniently studied macroscopically when the purpose is to discover the nature of energy exchange processes between a gas and its environment, or the behavior of a gas when it is cooled or heated.

Such problems are of very great interest as regards the entire technology of chemical systems in which gaseous reactions occur; they lie at the basis of the operating principles of all heat engines—systems that transform heat into mechanical energy. The branch of science that is concerned with the relationships between heat and work (applied energy) is called thermodynamics.

SYSTEMS, STATES, AND ENERGY

Quantitative magnitudes are of great importance in thermodynamics—for example, the heat energy associated with a substance at a certain temperature, and its relationship to the mass of that substance. It is also essential to define carefully the physical "boundaries" of the substance whose magnitudes are under discussion, which is usually referred to as a "system."

A system may comprise the liquid contained in a calorimeter, or the gas contained in a cylinder, or it may comprise the gas together with the cylinder that contains it, or even an area of space within which variable quantities of other substances can be introduced or withdrawn. In order to define such a system, it is necessary to assume that it has certain "boundaries" and can be isolated or controlled.

An isolated system is one that can be so constituted as to have no exchange of energy with its environment. It is impossible to establish an isolated system in practice, but a sufficiently close approximation can be established to facilitate the study of thermodynamics; the study of such systems can lead to conclusions applicable to actual systems.

In thermodynamics, it is not enough to define the boundaries and components of a system; it is also necessary to ascertain the magnitudes of certain variables of the system. Among these variables, the most important are mass, energy content, temperature, pressure, and volume. The values of these variables at any one time describe the thermodynamic state of the system at that time. It must be noted that not all the variables are independent of each other, and therefore, they cannot be arbitrarily established. One gram of pure hydrogen, for example, at room temperature and at a pressure of one atmosphere, must necessarily occupy a specific volume of about 12 liters (12,000 cm^3), and cannot be made to occupy 1 cm^3 without a change in temperature and pressure.

One of the variables that serve to describe a system is energy, which itself exists in many forms: kinetic, potential, mechanical, electrical, nuclear, surface, radiant, and so forth. Inasmuch as the variations of energy are important in the

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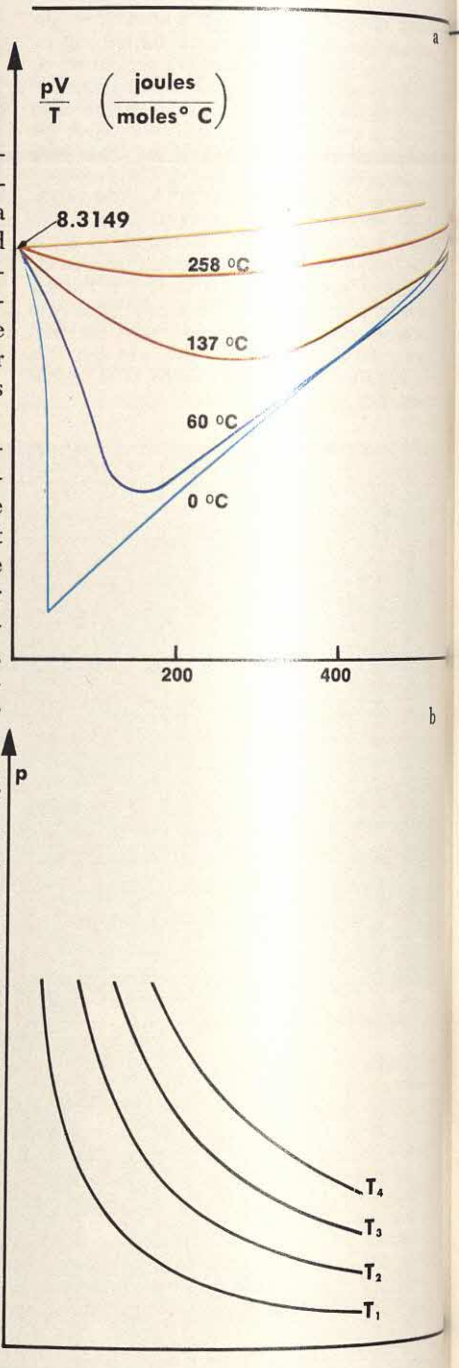


THE STATE OF A GAS—A three-dimensional drawing may be used to represent the state of a system if that system is a gas.

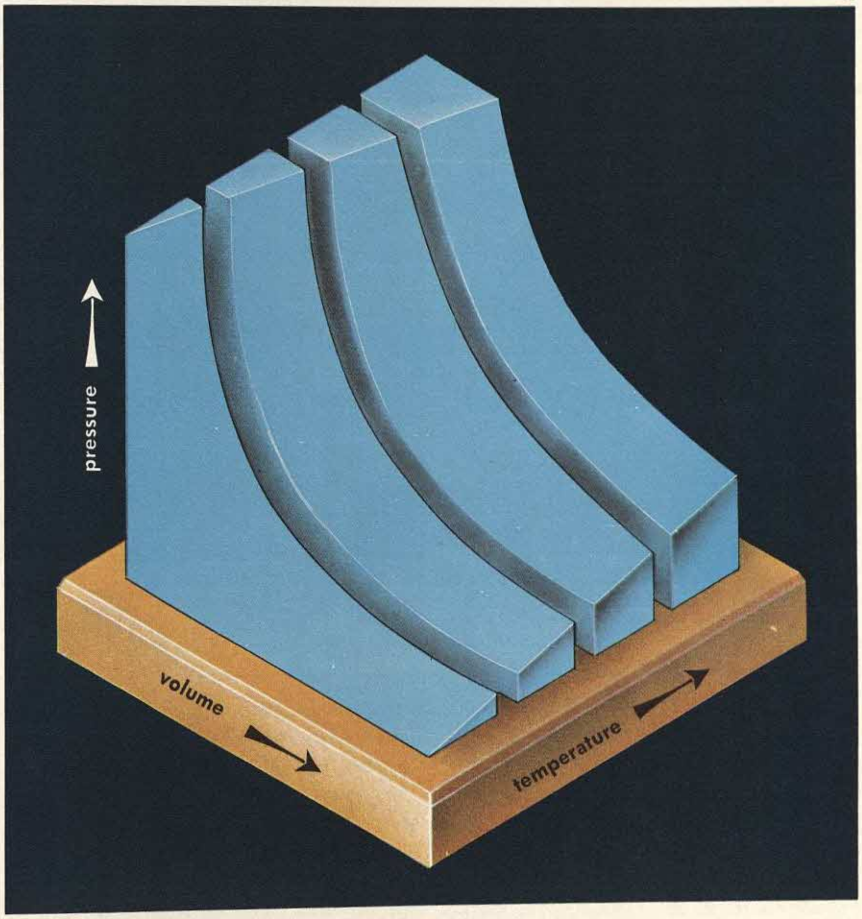
Through experiment, it can be demonstrated that the relationship between the pressure and the volume of a given mass of gas depends on its temperature. At a constant temperature and with a varying pressure, a certain curve will be obtained. This is a group of curves (Illustration 1a) showing what happens to a gram-molecular weight of carbon dioxide (44 grams) as its pressure changes. As the pressure approaches zero, all these curves tend toward the same value for the work-heat relationship, expressed as 8.3149 joules per mole-degree, a constant value for one gram-molecule weight of any substance, and designated algebraically as *R*. If the gram-molecular weight of any other gas is taken, different curves of pV/T will be obtained at various temperatures (Illustration 1b), but these curves will tend toward the same limit as p tends toward zero; this limit also has the value of R. It can, therefore, be said that, when relatively low pressures (small values for p) are involved, a range of pressures in which all real gases behave according to theory, the ratio pV/T has a constant value (R or 8.3149 joules per mole-degree) for one gram-molecular weight of any substance. This can be transposed to read $pV = RT$. Thus, with the temperature T constant, the curve relating to p and V (pressure and volume) will have the form of a hyperbola, inasmuch as the product of the constants R and T will have a constant value, and so will its equivalent, the product of p and V. Illustration 1b shows hyperbolas obtained for various temperatures, and is a graphic representation of Boyle's law, which states that at a constant temperature, the volume of a gas varies inversely with the pressure.

This law can be very effectively represented by making the curves form a surface of a three-dimensional diagram, shown in this stereogram (Illustration 1c).

Illustration 1d shows that by cutting the stereogram along planes parallel to the plane defined by the pressure and volume axes, sections are obtained showing the varying relationships between pressure and volume, each with the familiar hyperbola shown in Illustration 1b.

This graph (Illustration 1e), made by cutting the stereogram along planes perpendicular to the plane defined by the axes of the pressure and temperature, is a representation of Gay-Lussac's law, which states that if volume is constant, the pressure and temperature of a gas increase (or decrease) in direct proportion.

c



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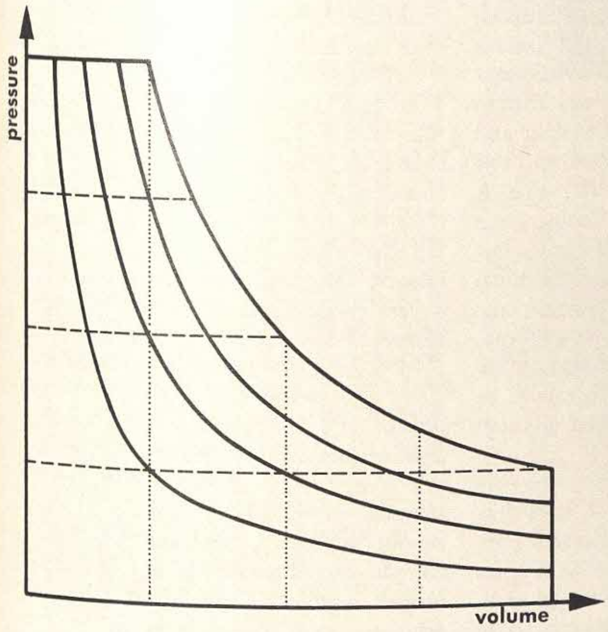

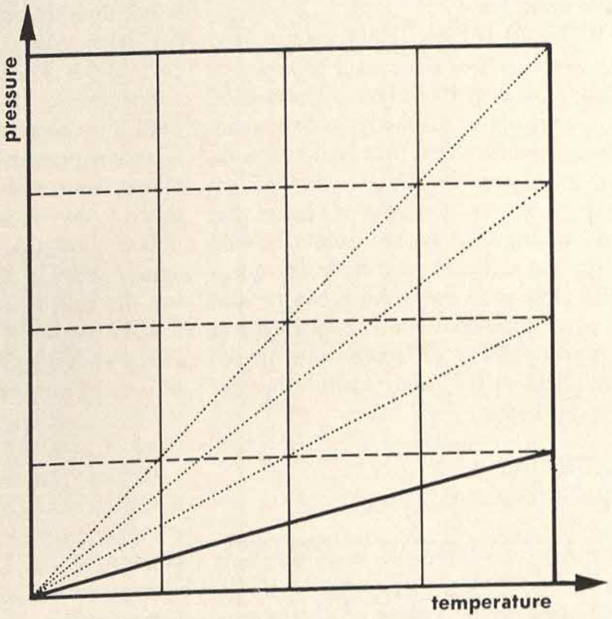

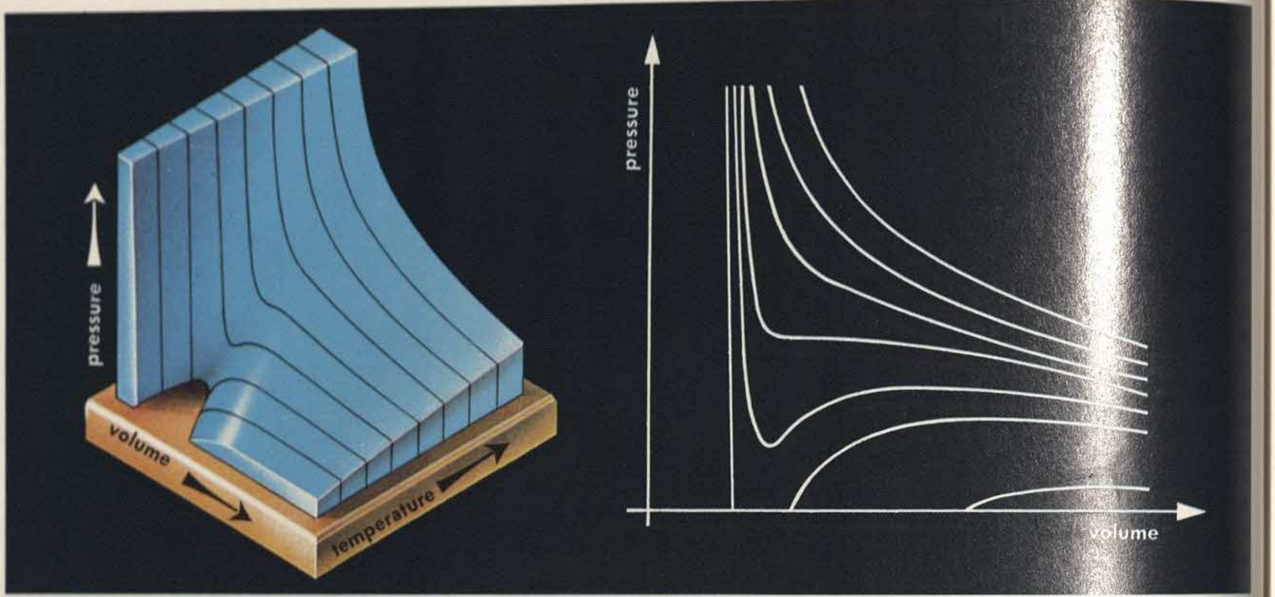

THE VAN DER WAALS EQUATION—The Dutch physicist Johannes Diderik van der Waals worked out in 1877 a modification of the earlier equations, so that they would apply to real gases instead of to ideal gases. This is a stereogram of the so-called Van der Waals equation, and also a graph made by cutting the stereogram along planes parallel to the plane defined by the pressure and volume axes; the two sketches are analogous to those in Illustrations 1c and 1d.

changes of state of a system, they must be measured. The variations of surface energy can be ignored, for example, if they are not relevant in comparison to other energy variations; but if the latter are quantitatively comparable to the variations of the surface energy, these variations must be taken into account—and this requires the measurement of all the variations.

It should be noted that neither heat nor work was listed among the various forms of energy that must be considered in describing a thermodynamic system. The reason for this is that heat and work are only ways in which a system exchanges energy, not types of energy that are exchanged. A system cannot be said to possess a certain magnitude (or quantity) of heat or work; but it can be said to possess a magnitude (or quantity) of energy, which it exchanges with its environment in the form of either heat or work or both.

EQUILIBRIUM IN THERMODYNAMICS

In order for a thermodynamic system to be in equilibrium, there must be a twofold equilibrium: among all the internal forces of the system (those forces exerted between its component parts, but that are isolated from the environment); and in the forces that cause interaction between the system and its environment. This equilibrium must, moreover, involve the system as a whole; if its components, for example, include two gases capable of diffusing into each other, the system is not in equilibrium until this diffusion has taken place. Similarly, the various parts of the system cannot be at different temperatures; there is no equilibrium until the temperature of the system and all its components has stabilized, and this temperature must also be the same as that of the environment. Temperature differences within the system usually disappear after a certain period of time; but the environment is not always controllable, and if the external temperature varies in the course of time, no equilibrium in respect to temperature may be attained for the system in that environment of instability.

In real systems, chemical factors may also affect the equilibrium. If a system contains hydrogen and oxygen at a temperature of 573° C (about 1,063° F), for example, it will only have attained equilibrium when the two elements have combined to form water and only the excess remaining after combination persists as a gas. Chemical equilibrium is the most difficult to attain in practice, because it sometimes takes considerable time; for example, oxygen and hydrogen do not combine at ordinary room temperatures and begin to combine very gradually at 300° C (572° F), finally reacting explosively at 550° C (1,022° F); once they have combined, water remains a very stable part of the system.

To sum up: Thermodynamic equilibrium means that the system under consideration is in mechanical, thermal, and chemical equilibrium. In most such systems variations in pressure and volume are also important; if a gas is a component, very slight variations can have a very pronounced effect. Temperature variations are also most important.

In order to represent graphically the states of a system in equilibrium, three-dimensional drawings are used, or else a two-dimensional section of such a drawing. It must be remembered that gases in practice do not always behave as they should in theory, and this sometimes complicates calculations; but the theoretical calculations provide a frame of reference for real situations.

THE FIRST LAW OF THERMODYNAMICS

the principle of the conservation of energy

At the beginning of the nineteenth century, classical mechanics had reached a high degree of perfection, especially in its application to astronomy. Scientists could predict accurately the motions of a planet and even the existence of unknown planets because of their gravitational attraction toward known planets.

Yet at this same period in the history of science, erroneous hypotheses were accepted concerning the nature of heat, its transfer, and the relationships between heat and work. Heat was then considered a kind of "caloric fluid," rather than a form of energy that can be transferred between bodies. Although a series of famous experiments early in the nineteenth century demolished these erroneous concepts, part of the present terminology and some of the units of measurement in the field of thermodynamics continue to reflect the influence of the discredited hypotheses.

Soon after the pioneer French chemist Antoine Lavoisier had shown the necessity of establishing quantitative laws, and had thus laid the basis for the principle of the conservation of mass (and therefore of energy), which governs chemical reactions, Benjamin Thompson (Count Rumford), an English physicist, broke important ground in 1798 by rejecting the caloric theory of heat. He asserted that heat is a form of motion—a conclusion he reached by observing, during the boring of a cannon barrel, the relationship between the work done and the heat produced. In 1799 Sir Humphry Davy, an English chemist, came to the same conclusion when he noticed that two pieces of ice melted much more quickly when they were rubbed against each other than when left to melt alone. The basic work, however, resulted from the systematic experimentation with various forms of energy (electrical, chemical, mechanical, and thermal) by the English physicist James Prescott Joule. He sought to establish, by means of accurate measurements, that an equivalence existed between all these forms of energy—and his results, based on an experiment conducted in 1843, appeared in a paper "On the Mechanical Equivalent of Heat" published in 1850. He was the first to discover a numerical coefficient that makes it possible to express, in the same units of measurement, two quantities that—although connected and interdependent—are physically different: mechanical work and thermal energy. This coefficient is defined as the mechanical equivalent of the calorie (the unit of heat required to raise the temperature of 1 gram of water 1 C°),

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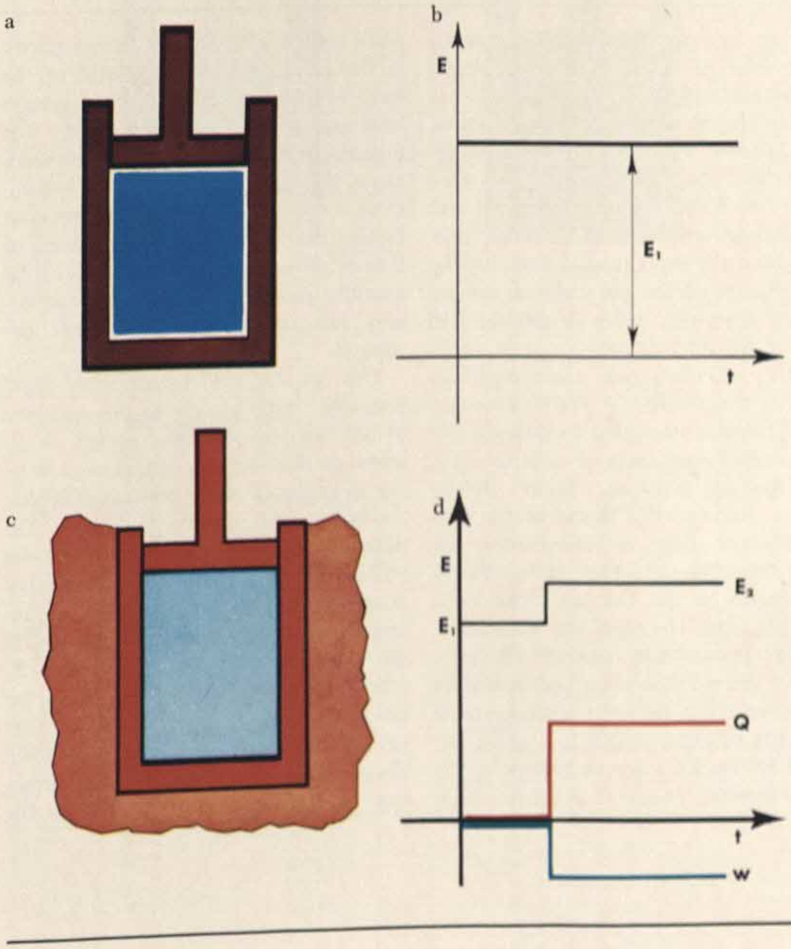
THE FIRST LAW OF THERMODYNAMICS—Illustration 1a shows a mass of gas enclosed in a cylinder fitted with a piston, comprising a closed system in equilibrium with its environment, the atmosphere. If there were no atmospheric pressure, the gas would expand within the cylinder and push the piston upward.

In Illustration 1b, the energy **E** of the system is plotted against time **t**, on the assumption that no change takes place and that the energy will remain constant, **E_1**.

Illustration 1c represents a change occurring at a certain instant of time; a hot body is placed in contact with the walls of the cylinder and a quantity of heat is transmitted through the walls to the gas, which expands, because its pressure now exceeds that of the atmosphere (the pressure of a gas increases with the temperature when the volume is constant). The piston is thus raised a certain distance and it has performed a certain quantity of work.

In Illustration 1d, the red line **Q** represents the quantity of heat, and the green line **W** represents the quantity of work (which can be measured in any of several units—thermal units, such as the calorie or British thermal unit, or mechanical units, such as the erg or joule). The variation or difference in energy between the beginning and the end of the process, **E_1** and **E_2**, is equal to the difference between **Q** and **W** (as measured from the base line).



2a

J. Joule

2b

H. Hemholtz

2c

G. R. Mayer

and its inverse is called the thermal equivalent of work. The fundamental contribution of Joule, however, was not merely the establishment of a relationship between these two units of measurement, but the experimental proof that these two forms of energy—thermal and mechanical—are equivalent. He thus presented the experimental basis for the formulation of the principle of conservation of energy, which is also the first law of thermodynamics.

Other scientists also made contributions to the problem. A French scientist, Marc Séguin, attempted to estimate the mechanical equivalent of heat in 1839. A German physicist, Julius Robert Mayer, formulated a theory of the conservation of energy in 1842. Perhaps the most thorough exposition of the theory was made by the German physiologist and physicist, Hermann von Helmholtz, in 1847. It was Joule, however, who most clearly proved that when heat and work are measured in the same units, the same quantity of either added to a given isolated system increases its energy by the same amount. To put it in another way, when such a system loses energy partly in the form of heat and partly in the form of mechanical work, that system loses as much energy as if the entire loss took the form of heat alone or of work alone. This phenomenon leads to a statement of the first law of thermodynamics: Energy can be exchanged in the form of heat or of mechanical work, but its total quantity remains constant, because energy can neither be created nor destroyed.

This law can also be expressed algebraically. If Q represents the quantity of heat that a controlled system is allowed to absorb from outside, and W is the quantity of work performed within the system and allowed to leave it, the difference between these two quantities will be equal to the change in the energy possessed by the system itself, represented by E_1 (the energy possessed at the beginning of the process) and E_2 (the energy possessed at the end of the process): $E_2 - E_1 = Q - W$. To sum up: the difference in energy between the two states of a system that has undergone a transformation is equal to the difference between the quantity of heat absorbed from outside the system and the mechanical work performed by the system on its environment. This principle is generally valid and is not limited exclusively to a system of specific dimensions.

The first law of thermodynamics, which states the principle of the conservation of energy, also serves to demonstrate that certain machines are not capable of functioning. These are machines that would, once started, continue to operate ceaselessly—so-called "perpetual motion" machines.

It is conceivable that a closed system may have a constant sum of energy—expressed in a certain state of volume, pressure, and heat, for example—and undergo transformation within itself, say, by increasing pressure and decreasing volume, all the while maintaining its constant sum of energy. It is also conceivable that such a system may undergo a second transformation that will return it to its initial state. In that case, the sum of these two transformations would constitute a cycle; if this cycle could continue indefinitely, change could take place indefinitely within the system without changing the total of the energy involved. In other words, an energy change in the first part of the cycle would be exactly compensated by an opposite energy change in the second part.

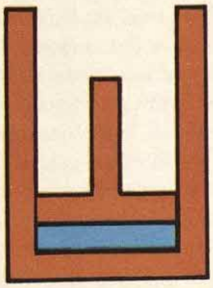
It is also conceivable that a system (or machine) could be devised to carry out a cycle so that the energy needed for the second part of the cycle (the part needed to restore the system to its initial state) would be less than the energy employed in the first part of the cycle. If this were possible, each time the cycle was repeated, some excess energy would be produced. However, this would contradict the first law of thermodynamics, which states that energy can neither be created nor destroyed.

The possibility of devising a system or machine capable of perpetual motion stimulated the imagination of man long before the basis was laid for the postulation of the principle of the conservation of energy. Long before that time it had become evident, after many attempts and many failures, that such a system could not be devised. This failure and its realization were, in a way, further evidence of the validity of the principle, which today is easy to accept. A century ago, however, its validity did not seem so irrefutable—especially because the principle, in turn, seemed contrary to the facts of astronomy as then known. Scientists, for example, could not understand the source of the sun's apparently limitless production of energy, which could be accounted for neither as the result of any chemical reaction nor as deriving from an endless reservoir of heat produced at some remote time by some unknown reaction. Scientists of that time were compelled to assert that this phenomenon was caused by something that could not be reproduced on Earth. Only after it was discovered that mass and energy were equivalent, and that thermonuclear reactions could release enormous quantities of energy, could the thermodynamic mechanism of the sun and the stars be explained and the most dramatic application of the principle of conservation of energy be reaffirmed. This principle, in fact, led directly to the realization of the equivalence of mass and energy.

3

PERPETUAL MOTION—These illustrations are meant to represent a system undergoing cyclic transformation, at the end of which the system is restored to its initial state. This is represented in Illustration 3a; in Illustration 3b, with the application of heat from the outside, work is performed (raising the piston); in Illustration 3c, work is performed on the system from outside (lowering the piston). In Illustration 3d, heat is lost to the outside, restoring the system to the state shown in Illustration 3a. If, as is assumed, the system carries out perpetual motion, at the end of the cycle its energy should be greater than it was at the beginning; and with a repetition of the cycle, which may be assumed to continue indefinitely, the quantity of energy would continuously increase and—if not drawn off—accumulate within the system (Illustration 3e). The impossibility of devising such a thermodynamic system in itself constitutes a proof of the validity of the first law of thermodynamics.

c



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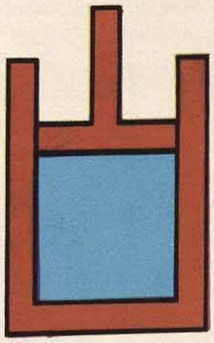

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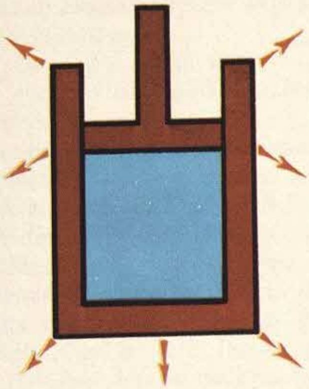

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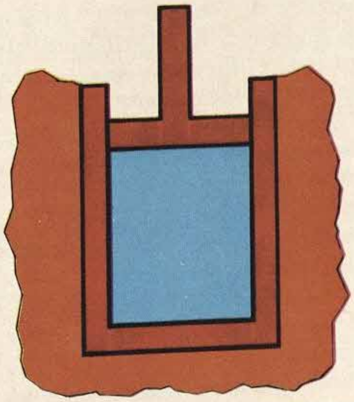

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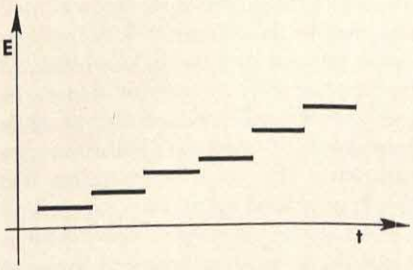


THE SECOND LAW OF THERMODYNAMICS

impossible and irreversible processes

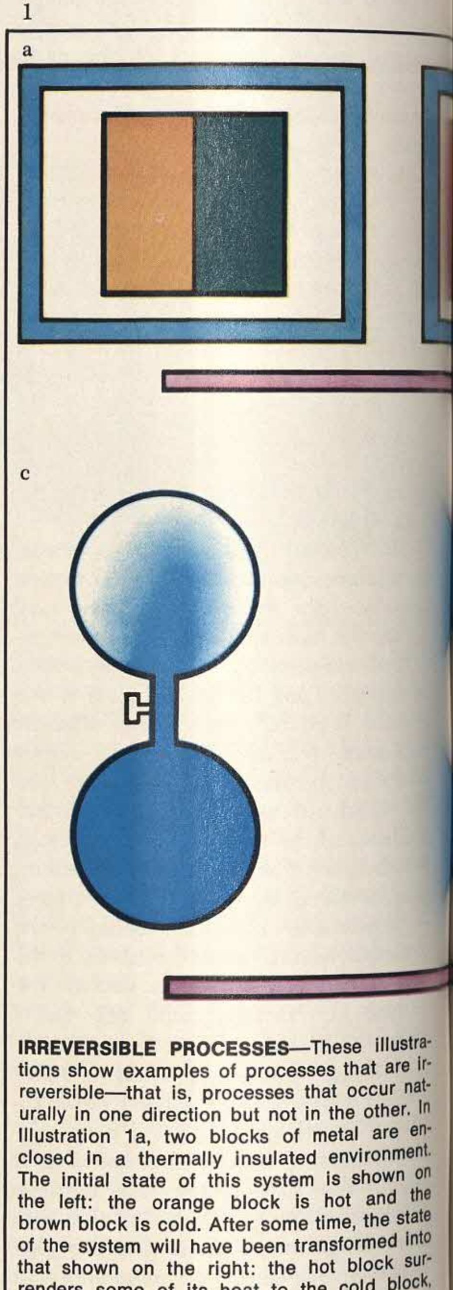
The science of mechanics is based on simple, easily verifiable principles that are among the fundamental laws of physics. In the same way, the science of thermodynamics, which is concerned with the exchange of heat and the transformation of heat into work, is based on fundamental laws; but these laws are more complex and are more difficult to verify. One such law is the second law of thermodynamics, which is primarily concerned with the limitations of the processes that take place within isolated systems. Although the second law is more complex than the first law—which is essentially only an application of the principle of the conservation of energy—it can be understood without too much difficulty, and is as universally valid as the first law.

IMPOSSIBLE PROCESSES

Some phenomena that can be imagined prove to be entirely impossible of fulfillment. Inasmuch as both hot and cold objects possess a certain amount of heat energy, for example, one may imagine that this energy could flow in both directions. If two steel blocks identical in size and shape are placed next to each other along one flat surface of each, and so isolated from the rest of the environment that no heat can be exchanged between the blocks and the environment, and if one of the blocks is hotter than the other, then after a certain amount of time the temperature of the two blocks will be the same, resulting from a flow of thermal energy from the hotter to the cooler block. Yet theoretically, it would be possible for thermal energy to flow from the cooler to the hotter block, increasing the temperature of the latter and also increasing the difference in temperature between the two blocks. Both everyday experience and experiments prove that this kind of flow never takes place; heat passes or is transferred only from a hotter to a cooler object, and never in the opposite direction. This is one way to state the second law of thermodynamics, and it was first so stated in 1850 by the German physicist Rudolf Clausius.

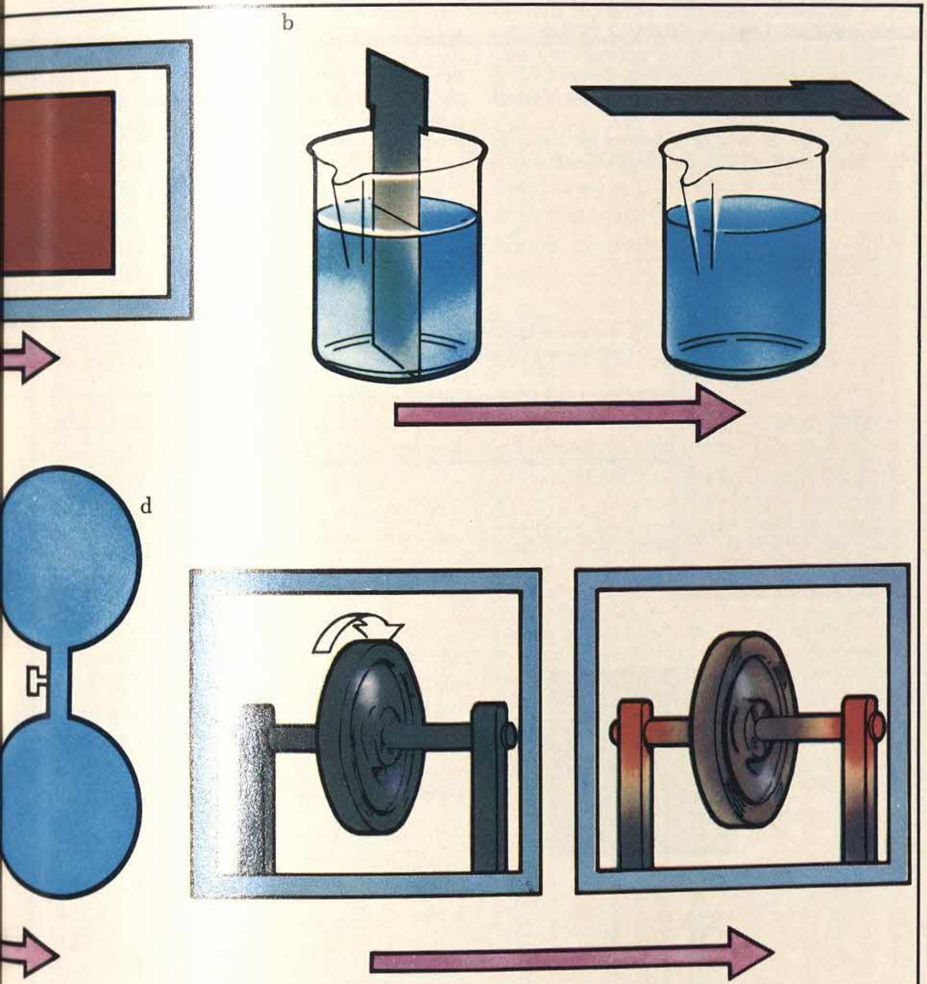
Any natural process that can occur in only one direction is known as an irreversible process. Another irreversible process involves the diffusion of fluids (liquids or gases) that are capable of mixing. A container is fitted with a removable divider and then filled with two different liquids, one on each side of the divider so that they do not mix. If the divider is then very slowly removed without disturbing either of the liquids, in a very short time the liquid in the container becomes a homogeneous mixture of the two liquids, without having been stirred or shaken. This kind of mixing, which also occurs in gases (for example, the air), results from the movement of the molecules of one component (liquid or gas) among the molecules of the other component, without the performance of any work (such as shaking). However, under no conceivable circumstance could the two components—in this case the two originally separated but now mixed liquids—again separate themselves, each on one side of the container, so that the divider could be reinserted between them. In other words, the diffusion of liquids and gases is another irreversible process.

A third and very important example of an irreversible process is that of the action of gases enclosed in a container. Two containers are placed in a controlled, thermally isolated environment so that they are not affected by changes in temperature; one of these containers holds a gas and the other is completely evacuated. If the two containers are then joined so that their contents mingle, the gas from the one container expands—without an increase in temperature, inasmuch as no work is performed—into the evacuated container. The result is two containers of gas at the same temperature. Under no circumstances will the gases again separate themselves and fill only one container, leaving the other as a vacuum.



IRREVERSIBLE PROCESSES—These illustrations show examples of processes that are irreversible—that is, processes that occur naturally in one direction but not in the other. In Illustration 1a, two blocks of metal are enclosed in a thermally insulated environment. The initial state of this system is shown on the left: the orange block is hot and the brown block is cold. After some time, the state of the system will have been transformed into that shown on the right: the hot block surrenders some of its heat to the cold block, and both have a temperature intermediate between the original temperatures of the two blocks. The arrow indicates the direction in

Finally, if a simple flywheel, which is suspended and free to rotate, is placed, while rotating at considerable speed, in an insulated environment, then after a time, because of the forces of friction, the wheel will stop rotating, and heat will be developed. In this change from kinetic to thermal energy, the total energy of the system—the wheel in its isolated environment—has not increased



which heat transfer naturally occurs.

In Illustration 1b, the divider in the beaker separates two different liquids—for example, water and alcohol—that can be mixed. When the divider is removed, without disturbing the two liquids, the molecules of each liquid will diffuse into the other, as shown in the container on the right. The two liquids cannot naturally separate again. As before, the arrow shows the direction in which the process naturally occurs.

In Illustration 1c, the lower portion of the container on the left contains a gas separated from an evacuated chamber above it. When the neck joining the two chambers is unplugged, the gas rushes into the empty space, with no change in temperature. It cannot be made to return naturally into one chamber, leaving a vacuum in the other.

In Illustration 1d, a flywheel rotating within an insulated space (on the left) gradually comes to a halt because of the forces of friction, which transform its initial energy into heat (on the right). Because this thermal energy remains within the system, the total energy of the system is unchanged; but the thermal energy cannot be used (without employing some external agency) to revert to mechanical energy and start the flywheel to rotating again.

or decreased; but the nature of the energy has changed. Again the opposite change will never occur; the heat energy will not change itself into kinetic energy, cooling and rotating the wheel. This mechanical process is irreversible.

THE CONCEPT OF ENTROPY

In these examples, in which irreversible processes have taken place within isolated systems, the total energy has always remained constant; the thermodynamic and mechanical quantities have changed, but the variations have occurred in different ways in each system, and it seems almost impossible to generalize these irreversible processes other than by describing them as irreversible. However, Clausius developed the concept of entropy, which refers to the property of a system in terms of its *available* energy—if the quantity of this energy tends to decrease, an increase in entropy is said to occur. Because irreversible processes always involve a decrease in the energy available for work (not all energy, of course), entropy tends, on the whole to increase.

Entropy is a function of the states of a system that depends on its variable thermodynamic quantities, such as temperature, pressure, and so forth. However, its special property is that, no matter what change occurs in an isolated system, its entropy may remain unchanged or increase, but can never decrease. This is another facet of the second law of thermodynamics. It must be understood, however, that it applies only to isolated systems, and not to parts of a system; for entropy may indeed decrease within one part, although its increase in the other part or parts will be likely to balance out to a total increase for the entire system. The practical aspect of entropy was expressed in Lord Kelvin's statement that it is not possible, in an isolated system, for a transformation to occur that will produce as much energy in the form of work as has been available in the form of heat. In everyday terms, this means that no heat machine—a system transforming heat into mechanical energy—can be completely efficient.

It can be shown that the change of entropy depends only on the initial and final states of a system; hence its change can be found for any process, reversible or not, by considering the heat that would have been absorbed in reversible changes leading to the same final state. When a process is reversible, the sum of all changes is zero; for any irreversible process, the sum is positive.

The three statements that can be made concerning change of entropy—that it depends only on the initial and final states, that it is zero for a reversible process, and that it is positive for an irreversible process—are of great importance, both for the determination of entropy and for the prediction of possible changes in systems.

PERPETUAL MOTION

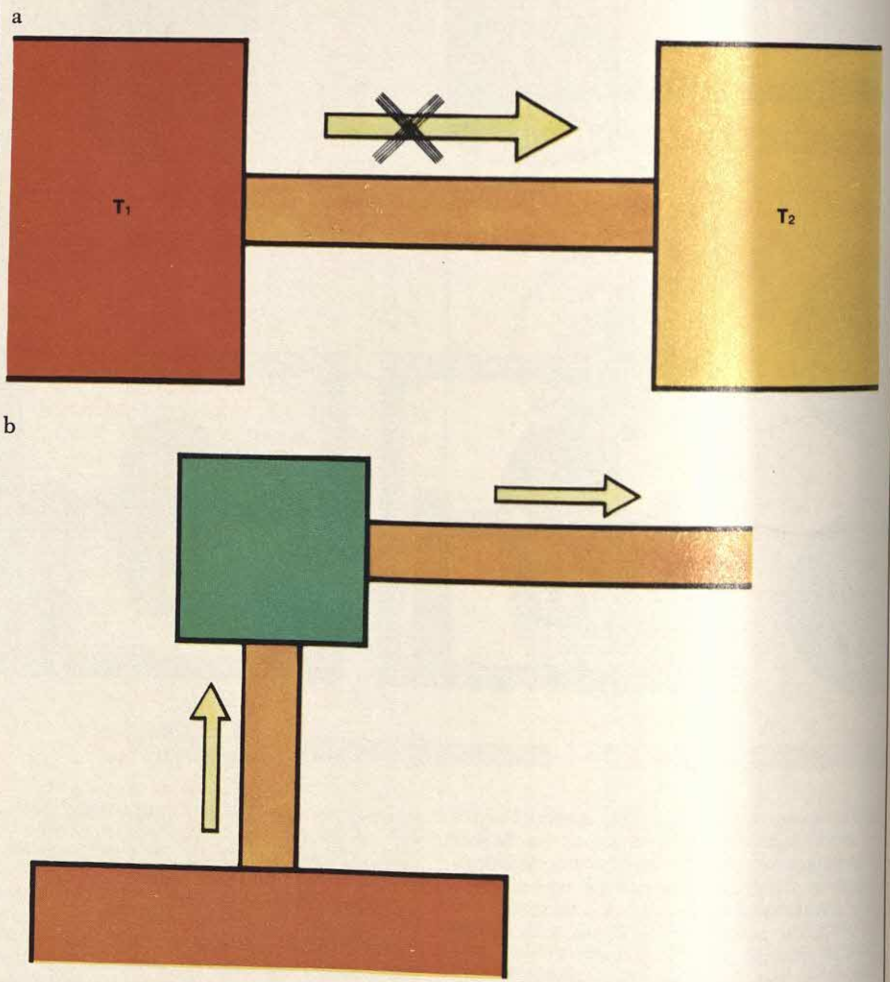
A cyclic process in which the net result is the restoration of all parts of the system to their initial states except for the removal of heat from a body, and the production of an equivalent amount of work, has been called a perpetual motion of the second kind. The impossibility of perpetual motion of the second kind is the essence of the second law of thermodynamics. This law may be stated in a number of different but fundamentally equivalent ways, one of which is: It is impossible to operate a cycle in which the only net effect is the absorption of heat from a body at constant temperature and the production of an equivalent amount of work.

No machine can be devised that will produce mechanical energy without absorbing heat energy. This statement conforms to the principle of conservation of energy, that is, the first law of thermodynamics, and in substance rejects the possibility of perpetual motion. This possibility is rejected in another sense by the second law of thermodynamics, which holds that whenever thermal energy is transformed into mechanical energy, it is impossible to absorb the entire quantity of the thermal energy from a single source and transform it into mechanical energy. If this were possible, mechanical energy could be produced by extracting the heat from seawater or from the rocks on the surface of the Earth, leaving them much colder than the environment. This unlimited source of thermal energy cannot be transformed into mechanical energy; and although men have sometimes attempted to envision this and similar possibilities, and it has been difficult to demonstrate that these visions cannot be realized, the proof can be found in the second law of thermodynamics.

2

THE SECOND LAW IN GRAPHIC FORM—According to Clausius, it is not possible to transfer thermal energy from a cold body T_1 to a hot body T_2, as shown by the arrow in Illustration 2a.

Illustration 2b shows a source of heat, at the base, flowing into an ideal machine (the square), which then transforms it into mechanical energy. According to Kelvin's version of the second law of thermodynamics, it is not possible for a machine to transfer the entire quantity of thermal energy so received into mechanical energy.



THE THIRD LAW OF THERMODYNAMICS

the formulations of Nernst and Planck

Thermodynamics is that branch of physics concerned with heat as a form of energy, and its effect on the molecules of matter and on other forms of energy. Thermodynamics applies to many fields, including mechanical engineering, low temperature physics, and chemical processes.

The basic laws of thermodynamics are contained in three laws. The first states that heat can be converted into work, and conversely work into heat, with the amount of work equal to the quantity of heat (expressed in terms of energy). The second states that when a free exchange of heat takes place between two bodies as a self-sustaining and continuous process, the heat must always be transferred from the hotter to the colder body.

The third law of thermodynamics states that every substance known to man has a definite entropy (an availability of energy to do work) that approaches zero as its temperature nears absolute zero—−273.16° C (−459.69° F). As the energy becomes unavailable, the entropy is said to increase. The variables in thermodynamic processes are entropy, pressure, temperature, and volume.

In many chemical reactions, the first law (conservation of energy) is not always evident and the energy is hidden in forms not easily recognized. However, energy cannot be spontaneously created but must always involve transformations of one type or another. For example, it is impossible to design an engine that will work without fuel or some other energy source. Neither will an engine be able to convert all of the heat obtained from fuel into mechanical energy. It can only convert a part of the heat into mechanical energy, depending on certain thermodynamic conditions.

Some of these conditions are inherent in the second law of thermodynamics, and they permit a more complete definition of the state of a system. Free energy and entropy, for example, are used to study equilibrium conditions in matter. Free energy must necessarily diminish in spontaneous reactions; otherwise, the reaction could not proceed.

The functions derived from the first and second laws only permit an incomplete definition of thermal characteristics or equilibrium constants, however. The absolute value of an equilibrium constant requires the determination of an integration constant apart from the functions themselves. Thus, variations in the entropy of a system can be predicted, but not the value that entropy had before or after the variation. This apparent limitation is overcome by means of the third law.

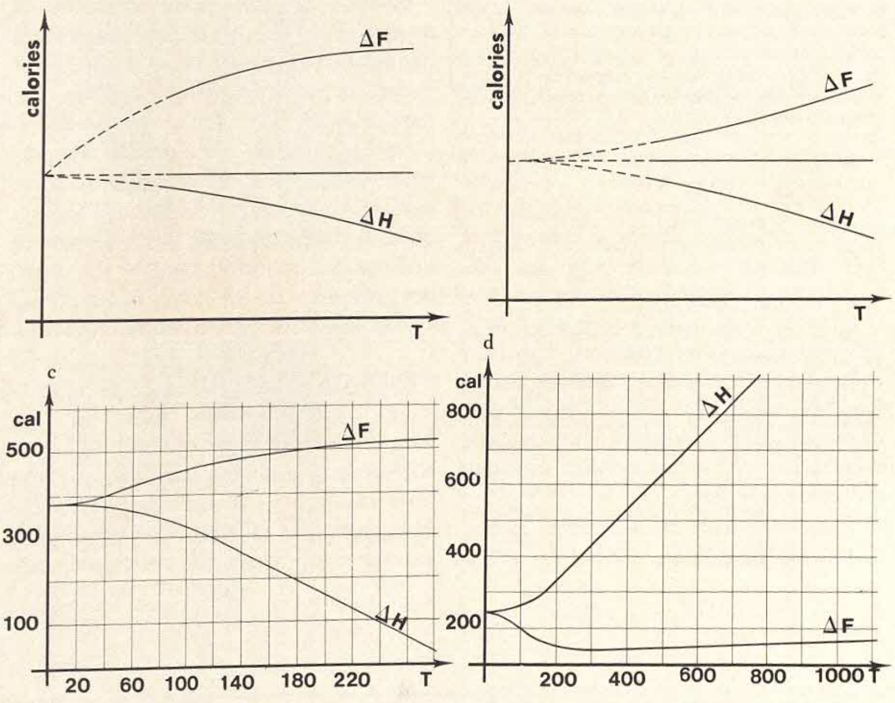
THE THIRD LAW OF THERMODYNAMICS

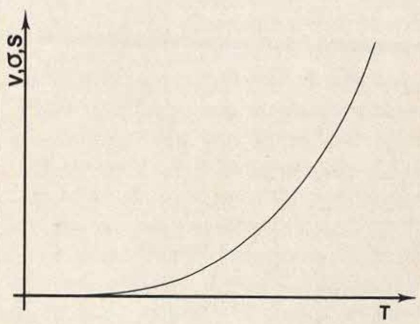
The third principle of thermodynamics was first formulated by the French chemist Le Châtelier in 1888. In his experiments, the changes of free energy that occurred in the reagents during a chemical reaction were studied. It became obvious that by determining an integration constant it would be possible to introduce this factor into the equation. In 1902, measurements of the reaction heat of various substances were examined, and it was found that the free energies underwent an increasingly small variation as the reaction neared absolute zero. In modern terms, a reaction produces a variation in free energy that depends on the temperature at which the reaction takes place. At low temperatures, the amount of variation of Gibbs's free energy is very close to the variation of Helmholtz's free energy.

1

GRAPHS OF THIRD PRINCIPLE—The discovery that the curves representing the variations of Gibbs's free energy (ΔF) and Helmholtz's free energy (ΔH) coincide at absolute zero is shown in Illustration 1a. In Illustration 1b, it is shown that the two curves tend toward the same limit values as the temperature T approaches zero, and with a horizontal tangent in both cases, as predicted by Nernst.

The curves in a real case are seen in Illustrations 1c and 1d; the previous curves were only ideal. In the previous illustrations, a dotted line represents the part of the curves closest to absolute zero. In practice, it is possible to plot a curve without such gaps if that becomes necessary. The variations of F and H in transforming white tin into gray tin are shown in Illustration 1c. The character of the curves agrees perfectly with the theoretical curves. In transforming diamond into graphite (Illustration 1d), the curves again agree with the third law of thermodynamics. The only discrepancy (a minor one) is that the positions of the two curves are inverted.





2

THERMODYNAMIC AND PHYSICAL PROPERTIES AT ABSOLUTE ZERO—The behavior of matter at temperatures near absolute zero is shown. Entropy, specific heat, surface tension, and coefficient of expansion are the various properties examined. The behavior of these properties is determined a priori from theory (particularly the third law), but can be verified in actual experiments. The theory cannot, however, predict the form of the curves representing the increase in magnitude as temperature increases. In this illustration, the absolute temperature T is considered to be plotted along the abscissa, while the ordinate represents some property such as volume V, surface tension σ, or entropy S.

This illustration, and the other facts postulated, permit the following statement of the third law of thermodynamics. The entropy of a solid or liquid at absolute zero can be either zero or finite, but never infinite. When it is zero, the solid must find itself in a pure state in accordance with quantum mechanics. By pure state is meant a perfect crystal without defects or admixtures of isotropic type. Stating the third law in this way takes into account all the special phenomena that modern techniques have uncovered.

This can be plotted on a graph with both free energies shown as curves that come together at absolute zero. In 1902, no hypothesis regarding the form of the two curves was made, but it was established that they did coincide. The German physical chemist Walter Nernst later concluded that the curves not only came together at absolute zero, but that they did so at the same value and with the same tangent.

The Nernst formula, or thermal theory, contained everything needed to establish that the value of entropy at absolute zero was the same for all matter. Other methods are, of course, possible in formulating the value of entropy.

OTHER FORMULATIONS

The German physicist Max Planck subsequently established the fact that the entropy of a substance was zero at absolute zero. This formula defined a substance as a crystalline solid. Other complex considerations show that liquids and gases can have entropy values that are very different from zero at absolute zero. Liquids then have special characteristics (high viscosity, for example) at very low temperatures, while gases behave differently at the same low temperatures. The variations in the quantum states of gas atoms and molecules can be determined by spectroscopic examination.

While measurements confirm that the entropy of gases or liquids is not zero, the entropy does not rise to infinity as might be expected The variation of the entropy ΔS is defined as the quotient of a quantity of heat ΔQ exchanged and the absolute temperature T at which this exchange takes place; that is, $\Delta Q/T = \Delta S$.

Planck's formula is independent of others, and permits several interesting deductions. For example, in a body cooled by adiabatic transformation, the temperatures that can be obtained become less and less as the starting temperature decreases. In other words, it is not possible to attain absolute zero. This fact is basic to the study of thermodynamics and to an understanding of the third law. It is why this principle is sometimes called the unattainability of absolute zero.

TESTS OF THE THIRD LAW

Numerous evaluations of the third law of thermodynamics have been made. These tests called for the measurement of the heat capacities of substances involved in reactions for which the entropy change had been measured independently by the change of ΔF with temperature. In the majority of cases satisfactory agreement has been found, but several exceptions have also been noted. To say that the exceptional substances are not perfect crystalline substances is not a satisfactory explanation unless an independent criterion of perfection is available.

The case of hydrogen is most interesting. According to certain rules of quantum mechanics, normal hydrogen may be considered to be a mixture of parahydrogen (hydrogen with nuclear spins in the opposite directions) and orthohydrogen (hydrogen with nuclear spins in the same direction). At low temperatures and in the presence of an effective catalyst, the orthohydrogen changes to parahydrogen; as absolute zero is approached, it becomes nearly pure parahydrogen.

If the heat capacity of the hydrogen is measured in the presence of a catalyst that maintains the mixture of parahydrogen and orthohydrogen in their equilibrium amounts, entropies at higher temperatures are obtained. These entropies are consistent with measurements conducted by other means. However, during measurements of heat capacity conducted in the absence of a catalyst, the normal hydrogen persists as a mixture (three parts orthohydrogen and one part parahydrogen) to very low temperatures.

Heat capacities measured in this way, coupled with the assumption of zero entropy at the absolute zero, lead to an apparent entropy at moderate or even high temperatures—and this is in disagreement (by about 4 cal/mole-deg) with the results of measurements made with the reactions of hydrogen. Therefore, if this value is used to calculate chemical equilibria, the pressure or concentration of hydrogen so determined can be in error by a factor of nearly 10. For a few other substances, the corresponding error can amount to as much as a factor of three. Nevertheless, in the great majority of cases, excellent agreement obtains.

LOW TEMPERATURES | how they are obtained in the laboratory

Extreme cold causes many substances to assume exceptional properties they do not exhibit normally. Some metals and alloys, for example, become superconductors at very low temperatures. Other substances, such as helium, that are normally viscous at low temperatures will lose this viscosity under extreme cold. These effects and the production of such low temperatures in the laboratory have resulted in the special branch of physics called cryogenics.

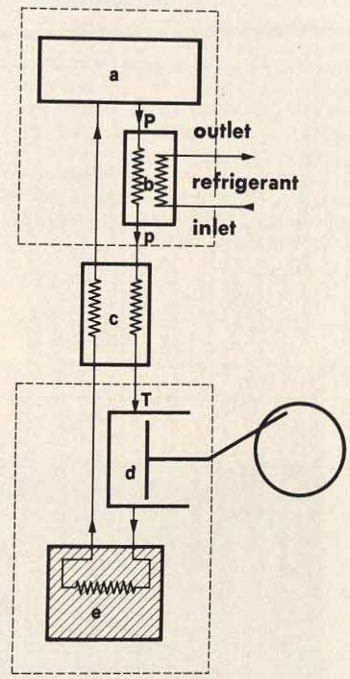
Often it is easier to study solids and liquids at low temperatures, where their properties are simpler to interpret and measure quantitatively. Some high-energy experiments in nuclear physics actually depend on cold, which is used to liquefy the gases that fuel rockets and missiles.

The equipment needed to produce low temperatures (several tens of degrees below zero Centigrade) was developed for the most part in this century, enabling researchers to liquefy many gases, including carbon dioxide and some hydrocarbons. At first some gases were considered incompressible, even at low temperatures, but these can now be liquefied as well. The more important of these gases, and the last to be liquefied, were helium, hydrogen, oxygen, and nitrogen.

Those temperatures between 50 and 90° above absolute zero were first thought to be extremely low temperatures. However, when hydrogen was subsequently liquefied (1898), the term low temperature came to mean that on the order of 10° absolute. It dropped again when helium was liquefied and cooled to 1° absolute. In 1922, temperatures of 0.726° absolute were obtained by evaporating liquid helium, and the Kelvin scale came into wide use (where $K = C + 273°$).

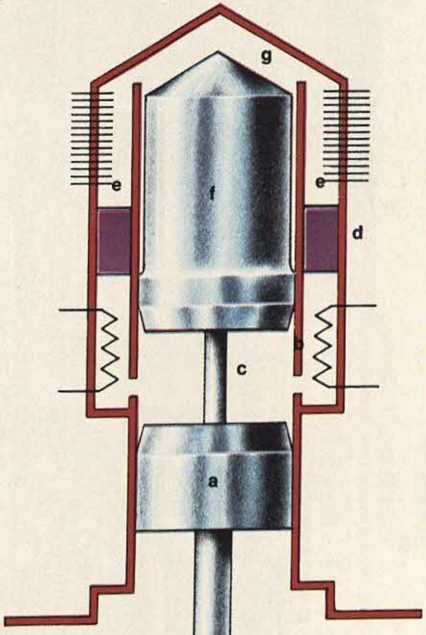
A few years later, an entirely new method made it possible to obtain still lower temperatures. This method, the adiabatic demagnetizing of paramagnetic crystals, is widely used today where experiments require temperatures below 1° K. In recent years, experiments actually have been made at temperatures below .001° K.

1



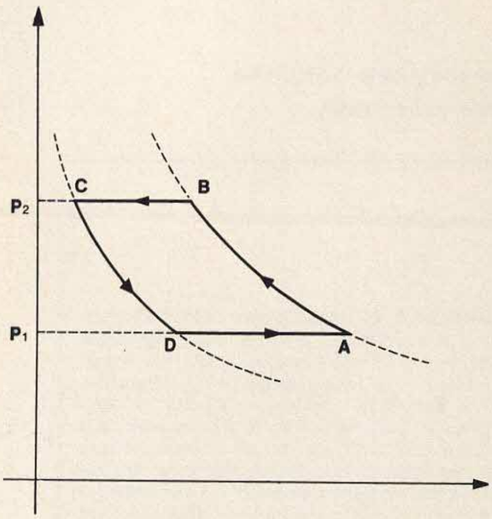
PRINCIPLE OF LIQUID AIR REFRIGERATOR—It is possible to produce liquid air in the laboratory with this system, which consists of a cold part **e,** hot part **a** and heat exchanger **c.** The refrigerant consists of air that is 'compressed isothermally at **a** to a pressure **p.** The upper heat exchanger **b** uses an external fluid to maintain the constant temperature. The refrigerant is then precooled in the heat exchanger **c** with the refrigerant that has been discharged from the cold part **e.** The refrigerant is now at a high pressure **p** and low temperature **t.** At **d** the refrigerant is isothermally expanded and brought to a low pressure. In the cold part, the refrigerant may be used to cool some external air, eventually liquefying the air. Finally the refrigerant is returned to the compressor at a low pressure to renew the cycle.

2



MECHANICS OF LIQUID AIR REFRIGERATOR—More details of the liquid air refrigerator are shown in this illustration. Actually, it is a small, compact, and relatively simple device. The piston **a** serves to compress the gas to be liquefied, the refrigerator or heat exchanger **b** cools it isothermally, and the regenerator **d** absorbs the heat produced into its porous walls. The regenerator actually takes the place of the heat exchanger shown in Illustration 1. The gas next passes into the cavity **e,** where it expands (piston is withdrawn). The piston is insulated and the gas to be cooled expands into the conic area **g,** which has finned outer walls that permit heat exchange. The gas to be liquefied (air) passes along the other side of these walls. The piston then pushes air through the regenerator, which is cooled, and this air returns to the piston chamber to begin the refrigeration cycle once more.

3



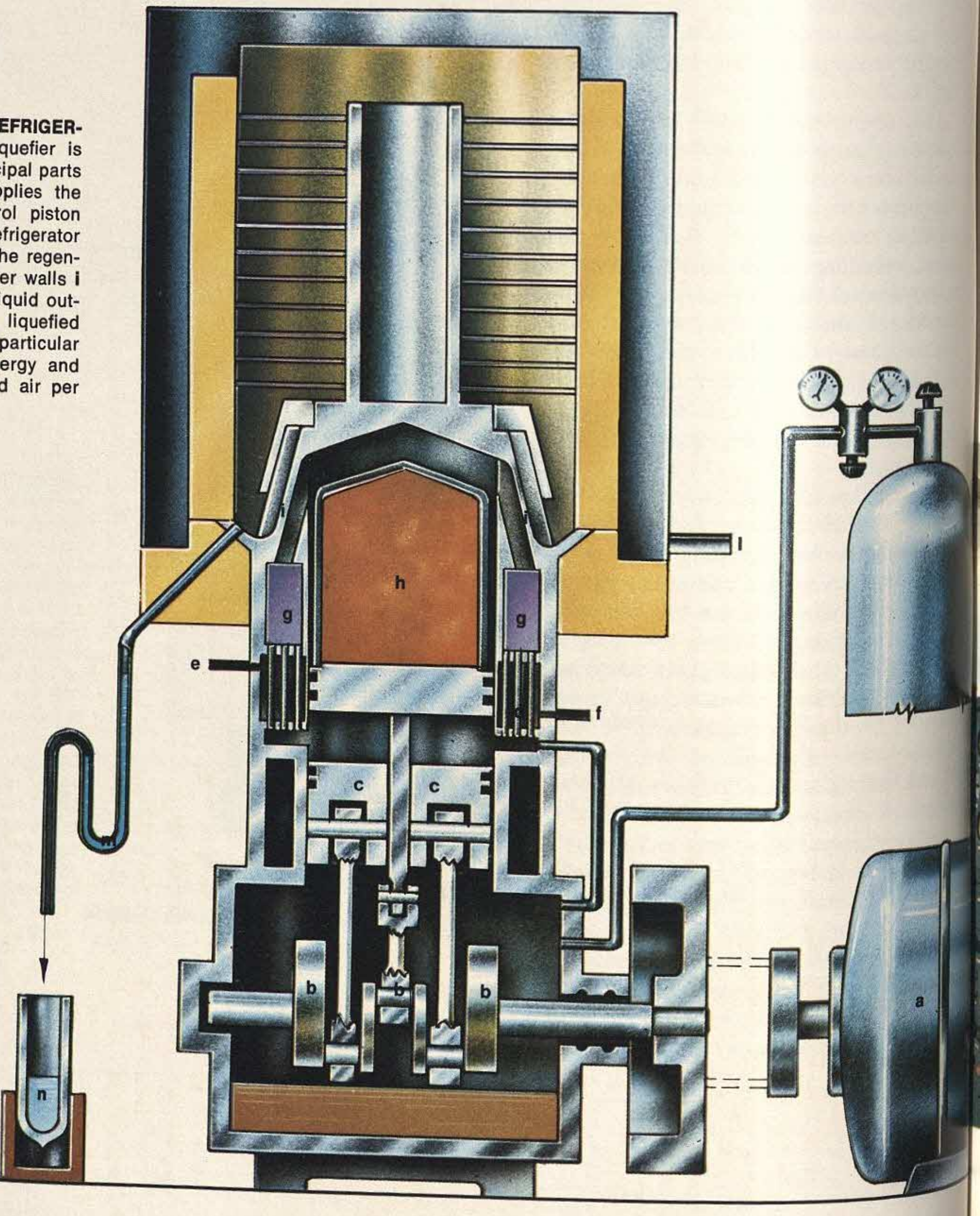
THERMODYNAMIC CYCLE—The cycle shown represents the steps used in the cooling process in Illustration 1. The cycle begins at **A** and undergoes isothermal compression to **B** (**a** and **b** in Illustration 1). From **B** to **C** the refrigerant is cooled at constant pressure (**c** of Illustration 1). From **C** to **D** there is an isothermal expansion (**d** of Illustration 1) and finally **D** to **A** depicts the return of the refrigerant through the cold part back to the compressor. The cycle has been somewhat idealized, since compression is not perfectly isothermal and heat exchange does not occur at constant temperature.

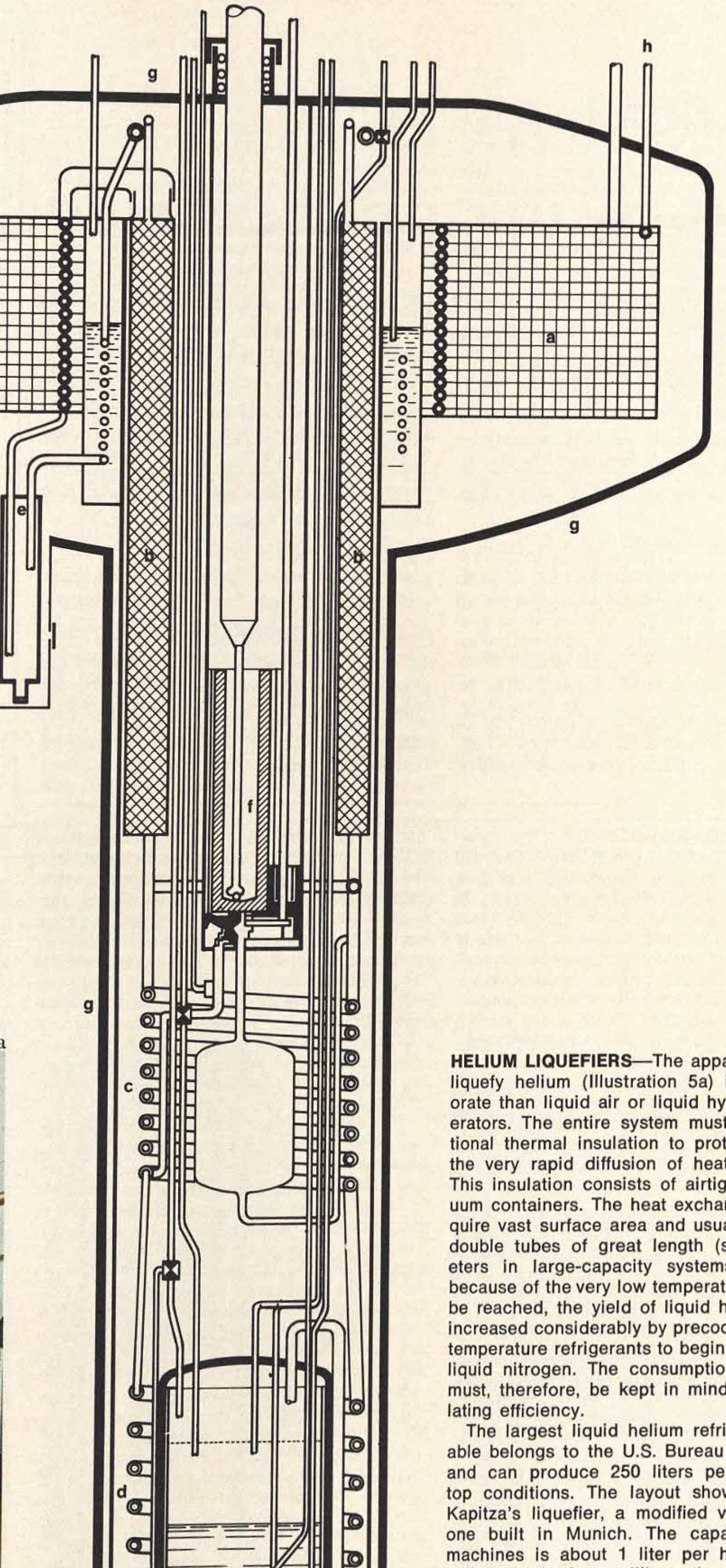
For these reasons, it is difficult to correlate low temperatures in different areas of research. Generally, it is understood that low temperatures refer to that range in which it is possible to liquefy so-called incompressible gases (helium). Extremely low temperatures then are those obtained only by means of adiabatic demagnetization. This cooling method was suggested independently by the Dutch physical chemist Peter Debye and the U.S. physical chemist William Giauque.

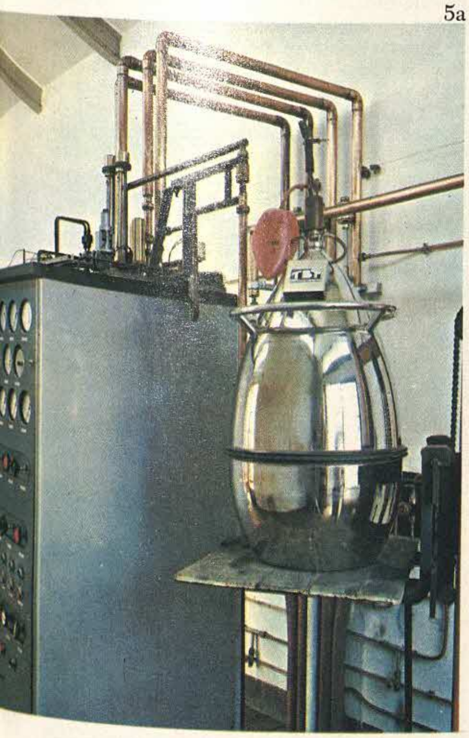
The equipment used to obtain low temperatures in the laboratory is shown in the illustrations. The various methods are many, but generally can be classified as either open- or closed cycle. The machines use compressed vapors or isoentropic expansion; and the refrigerators described can liquefy air or helium.

4

CROSS SECTION OF LIQUID AIR REFRIGERATOR—An actual refrigerator or liquefier is shown in cross section with the principal parts indicated. An electric motor **a** supplies the energy, crank mechanisms **b** control piston movement, and the external fluid refrigerator **d** has one inlet **e** and one outlet **f.** The regenerator **g,** piston **h,** and piston chamber walls **i** are also shown. The air inlet **l** and liquid outlet **m** complete the apparatus. The liquefied air is collected in a container **n.** This particular refrigerator consumes very little energy and can produce about 7 liters of liquid air per hour.







HELIUM LIQUEFIERS—The apparatus used to liquefy helium (Illustration 5a) is more elaborate than liquid air or liquid hydrogen refrigerators. The entire system must have exceptional thermal insulation to protect it against the very rapid diffusion of heat that occurs. This insulation consists of airtight metal vacuum containers. The heat exchangers also require vast surface area and usually consist of double tubes of great length (several kilometers in large-capacity systems). Moreover, because of the very low temperatures that must be reached, the yield of liquid helium can be increased considerably by precooling with low-temperature refrigerants to begin with, such as liquid nitrogen. The consumption of this gas must, therefore, be kept in mind when calculating efficiency.

The largest liquid helium refrigerator available belongs to the U.S. Bureau of Standards and can produce 250 liters per hour under top conditions. The layout shown is that of Kapitza's liquefier, a modified version of the one built in Munich. The capacity of such machines is about 1 liter per hour of liquid helium. In the layout (Illustration 5b), the principal parts are heat exchangers **a** to **d,** liquid nitrogen refrigerator **e,** piston **f,** and gas chamber **g.** The inlet **h** for the helium gas, which must arrive at a pressure of 30 atmospheres, and the container **i** to collect the liquid helium complete the apparatus.

HELIUM AT LOW TEMPERATURES

two liquid phases

For every rule, it seems, there is at least one exception. For liquids, the exception is helium. Laws applying to the nature and characteristics of liquids are valid for all liquids except helium at extremely low temperatures. At such temperatures helium displays some characteristics that have not been found in any other substance.

These characteristics were gradually and steadily examined through experimentation after the first liquefaction of this gas.

Because the element helium is very rare, experiments on the properties of helium were not frequent. It is interesting to note that helium was discovered in the sun in 1868, by means of a line observed in the spectrum, before it was found on the Earth. However, later that same year it was discovered on the Earth as the emanation of an igneous rock that contained radioactive substances. Since the atmosphere contains only five parts per million of this gas, it is as difficult to extract it from the air as from volcanic emanations or radioactive rocks.

Today it is possible to obtain considerable quantities of helium from natural gases that contain more than 1 percent of the gas by volume. Only after the supply of helium no longer constituted a problem did it become possible to use this element for experiments and thus obtain a better knowledge of its extraordinary properties.

THERMAL SUPERCONDUCTIVITY—The determination of the thermal conductivity of helium led to this surprising discovery: helium II possesses a very high thermal conductivity. In fact, its conductivity is about a million times greater than that of copper, which has one of the highest thermal conductivities among all the common substances. In absolute terms, helium II is the substance with the greatest known thermal conductivity. The first experiments made to determine its value were carried out by immersing a pair of plates in liquid helium. One of the plates was then heated and the temperature of the other was measured to determine the rate at which the liquid conducted the heat. The apparatus was sensitive enough to determine the thermal conductivity of helium I, but it could give no measurable temperature difference for helium II. The thermal conductivity of helium II could be measured only by the apparatus shown here. A thermally insulated container with a broad, closed base and a narrow, capillary tube opening at the top is placed upside down in a bath of liquid helium.

This vessel contains an electrical resistance that, when current is passing through it, can heat the liquid in which it is immersed. If the liquid level inside and outside the container is the same, the temperature on either side of the container also must be the same. Any difference in temperature would produce a pressure difference. For example, if the heating due to the resistance causes the helium inside the container to rise in temperature, a vapor tension is produced inside the container and the helium level in the container is forced below that of the open bath.

When the electric resistance is switched on, the helium in the container is heated. Equilibrium with the external liquid can be reached only through the capillary tube, since only a negligible amount of heat can be exchanged through the walls of the container, which was constructed from insulating material. The experiment shows, even when moderate quantities of heat are involved, that the flow of heat through the liquid filling the capillary tube is extremely rapid: this, quite obviously, corresponds to a very high coefficient of thermal conductivity.

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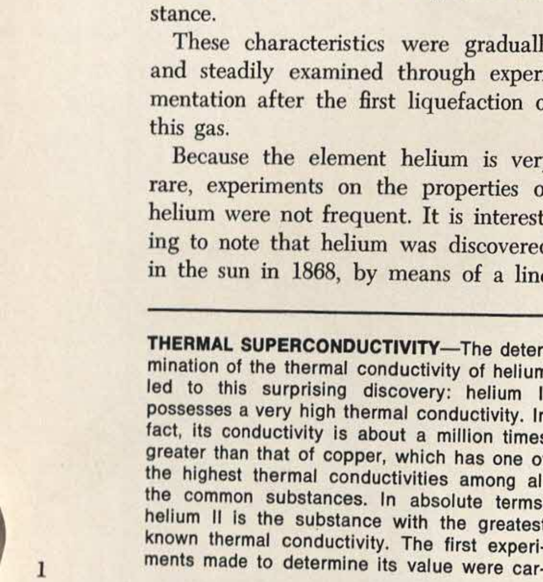
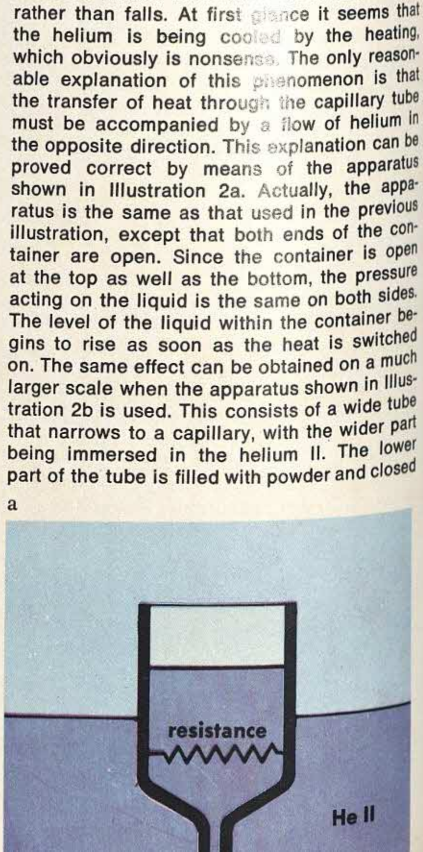
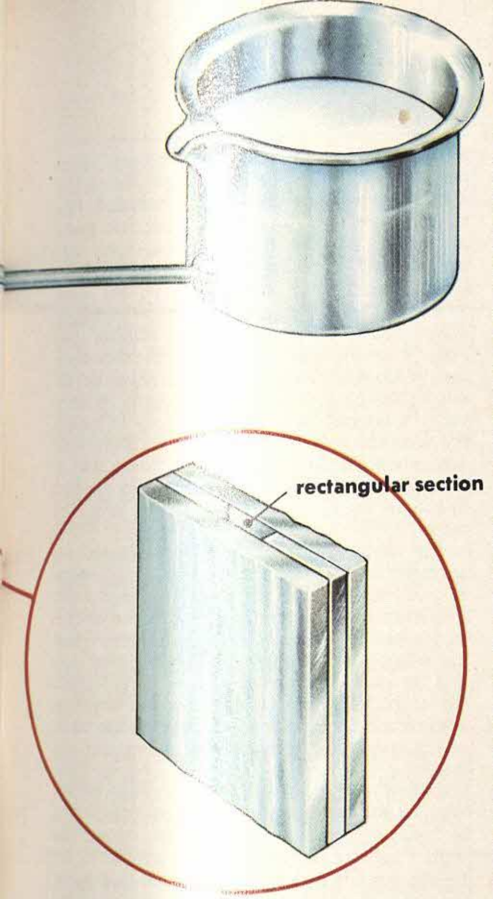


2

THE FOUNTAIN EFFECT—The experiment in the previous illustration yields surprising results when it is carried out in certain conditions of temperature. Specifically, when the helium inside the container is heated, sometimes the helium level within the container rises rather than falls. At first glance it seems that the helium is being cooled by the heating, which obviously is nonsense. The only reasonable explanation of this phenomenon is that the transfer of heat through the capillary tube must be accompanied by a flow of helium in the opposite direction. This explanation can be proved correct by means of the apparatus shown in Illustration 2a. Actually, the apparatus is the same as that used in the previous illustration, except that both ends of the container are open. Since the container is open at the top as well as the bottom, the pressure acting on the liquid is the same on both sides. The level of the liquid within the container begins to rise as soon as the heat is switched on. The same effect can be obtained on a much larger scale when the apparatus shown in Illustration 2b is used. This consists of a wide tube that narrows to a capillary, with the wider part being immersed in the helium II. The lower part of the tube is filled with powder and closed

a





3

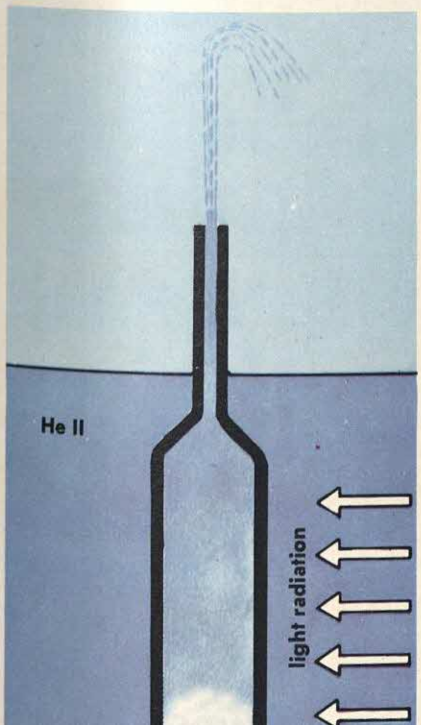
SUPERFLUIDITY—Another special characteristic of helium II is superfluidity. At very low temperatures helium does more than become a superconductor; its viscosity is reduced to extremely low values. Measurements of its viscosity were carried out by different methods. The earliest experiments were made with the rather primitive method of suspending a disk within the liquid and causing it to oscillate. In later experiments the liquid helium was made to flow through capillary tubes or through conduits formed of two parallel plates of glass placed very close to each other. This latter experimental arrangement was adopted by the Soviet physicist Peter Kapitza in 1941.

The upper vessel in this illustration contains helium; it communicates with the lower vessel by means of a conduit that narrows at a certain point, assuming a rectangular cross section. This section of the conduit consists of two parallel plates of glass kept a small distance apart by two lateral distance pieces (see enlarged detail). The helium can flow from the upper vessel to the lower one; the speed with which the transfer is made depends not only on the quantity of helium, but also on its viscosity and the distance between the two glass plates. When helium I is used for the experiment, the speed of transfer is slow; with helium II, on the other hand, it is very rapid. The glass plates are flat and, in the absence of the distance pieces, the two plates can be brought together until the distance between them is only 0.0005 mm. Helium I takes many minutes to flow through so small an opening (normal liquids would take a much longer time because of their greater viscosity), but helium II will pass in a matter of seconds. The experiment can be carried out in two operations: the upper vessel is filled first with helium I, and later with helium that has cooled until it has become helium II. The point to note is that the viscosity of helium is reduced by as much as 1,500 times as soon as the lambda point is passed. At a temperature of 1.6° K, helium II has a viscosity of no more than 10 micropoise (the poise is a unit of viscosity; its dimensions in the cgs system are g/cm sec). This means that the viscosity of helium II is about one twentieth the viscosity of gaseous helium, and about one ninth the viscosity of gaseous hydrogen. As is known, gaseous hydrogen is the least viscous substance known at ordinary temperatures.

The viscosity of gaseous hydrogen diminishes at very low temperatures and becomes comparable to that of helium II; but the hydrogen is a gas, while helium II is liquid. Even the most fluid liquids always have a viscosity about a thousand times greater than that of the gases. The low viscosity of helium II is due to an arrangement of the atoms that is very similar to the one postulated for an ideal gas. A contribution to the superfluidity of helium II is also made by its exceptionally low density, which constitutes proof of the great distance separating the molecules.

with a tuft of cotton wool. The powder absorbs energy when it is illuminated and thus heats the helium contained in the wider part of the tube. As a result of the flow in the direction opposite to that of the propagation of the heat, the helium is now projected violently upward and passes through the capillary tube, from which it issues in the form of a spout. Appropriately, this phenomenon is known as the fountain effect.

b



THE TRANSFER FILM — Another exceptional phenomenon associated with helium II is the formation of a film of liquid on the surface of the vessel in which the helium is contained. This film can cause considerable quantities of the liquid to escape. The helium here is put into a double-walled glass container in which the inner wall is silvered. As indicated, a film of helium forms along the walls, moves upward inside the container, and then descends along the outer surface. If the section of the container is reduced in size, the speed of transfer accelerates because the circumference of the section from which the film detaches itself becomes predominant with respect to its surface. The graph shows rapid diminution once the transfer takes place.

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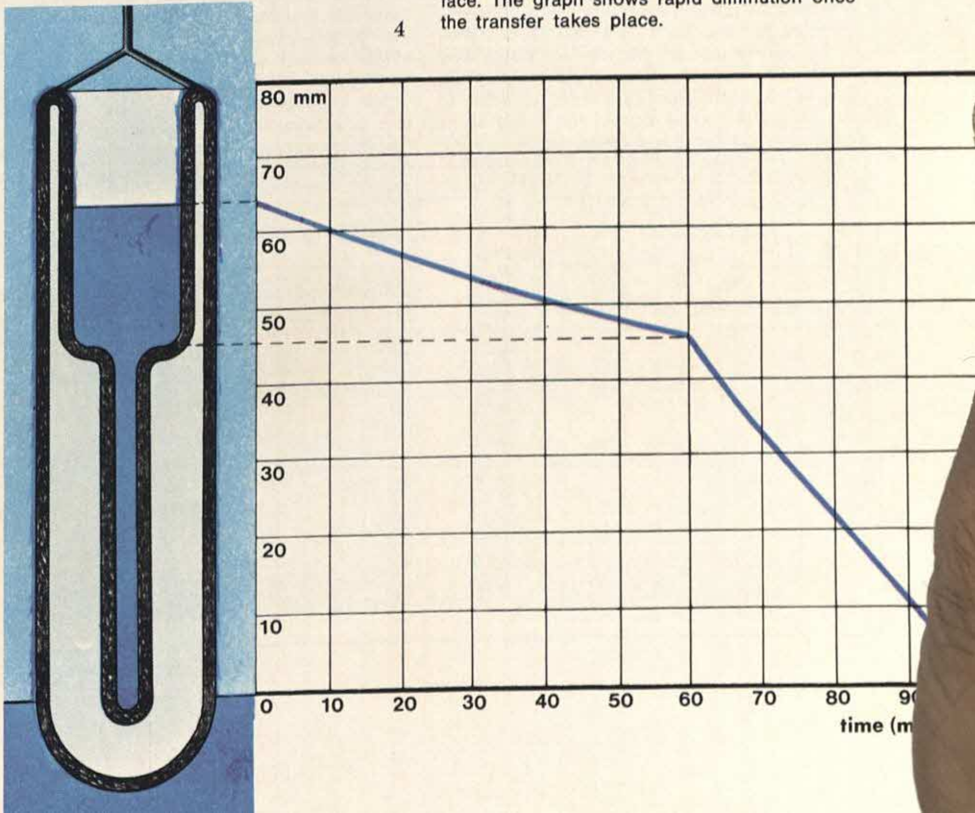

THE PHASE DIAGRAM—This illustration shows the curves that represent the conditions of pressure and temperature in which two phases of a substance can coexist. The phase diagrams of all substances have a triple point where the three phases (solid, liquid, and gas) of the substance can coexist. In the case of helium, however, there is no such point because the solid cannot with stability coexist with the vapor.

If solid helium and helium vapor are brought together, one of the two phases will disappear by turning into the other or by becoming liquid. Depending on the prevailing temperature and pressure, some of the solid will fuse, or the vapor will condense, until the coexisting phases are either liquid and solid or liquid and gas.

Another surprising feature of the phase diagram of helium is the presence of two liquid phases. The one that is stable at higher temperatures is called helium I, while the one that is stable at lower temperatures is called helium II. Many substances possess two distinct phases characterized by different organizations of their atoms; in other words, by different crystalline structures. However, this never occurs in a normal liquid because there is no bond between the individual atoms that obliges them to assume some fixed position. In liquid helium, on the other hand, the existence of these two phases reflects different organizations of the molecules. Another peculiar characteristic of helium is the fact that, regardless of the temperature, it never solidifies at the pressure corresponding to its own vapor pressure (this is another way in which the absence of a triple point is dramatized). The phase diagram shows very clearly that a pressure of at least 26 atmospheres is needed to solidify helium even at the lowest temperatures.

The density of helium also presents an anomaly. In fact, the liquid phase of helium is much lighter than might be expected from a calculation based on the diameter and weight of the helium atom. Actually, it is known that the difference in behavior between a real gas and an ideal one makes it possible to obtain the covolume of the gas; that is, the effective volume of its molecules or atoms. In the case of liquid helium, however, the atoms are not arranged at intervals corresponding to their diameter; instead, they are much farther apart. Many of helium's properties can be interpreted by applying the laws of quantum mechanics rather than those of classical mechanics, although the latter are quite sufficient to explain the properties of all the other gaseous substances. For this reason it is said that liquid helium is a quantum liquid.

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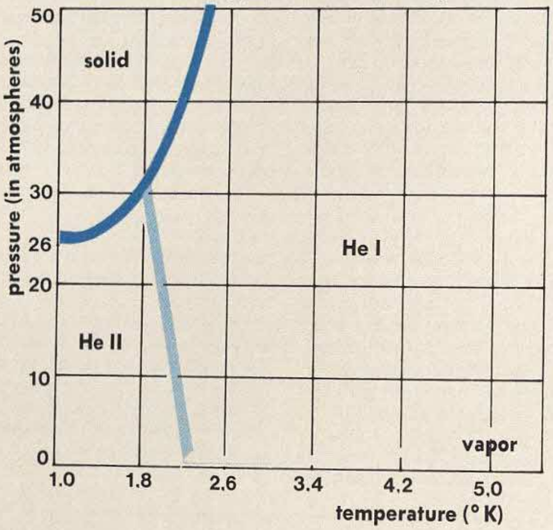


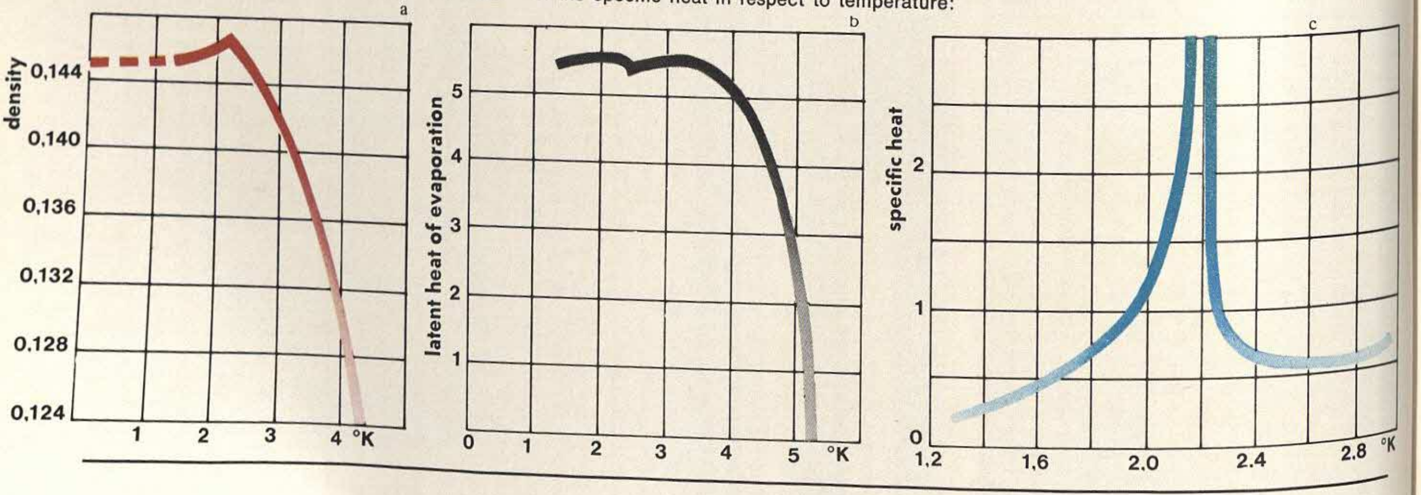
6

THE LAMBDA PHENOMENON—The discovery of the two phases of liquid helium was made gradually as the studies of its physical properties progressed.

Density was the first characteristic of liquid helium to be analyzed (Illustration 6a). It shows a maximum value at the point where the temperature of the liquid falls below about 2.2° K at normal pressure. Water also displays a maximum value of the density at a temperature of 3.95° C (about 39.2° F), but the variation of the density on either side of the maximum is quite gradual. In the case of liquid helium, however, the variation is abrupt and the diagram comes to a sharp peak. This fact is an indication of a change of phase in the substance being examined.

Illustration 6b plots the latent heat of evaporation; that is, of the amount of heat needed at various temperatures to cause a liquid to evaporate. Here again there is a sudden variation at the same temperature at which the abrupt variation of density occurs. This strongly confirms the variation of the liquid phase.

The third proof, and the most significant one, is provided by its specific heat. Illustration 6c shows the curve marking the variation of the specific heat in respect to temperature: at a temperature of 2.2° K the value of the specific heat becomes infinite. This phenomenon occurs only at a point where a phase transition is taking place. The complex of these phenomena that demonstrate the presence of two liquid phases is commonly known as the lambda phenomenon, with the lambda point defined as the value of the temperature at which the transition phenomena occur. The lambda point varies with the pressure. Another look at the phase diagram discloses that the transition temperature becomes lower as the pressure increases.



TOWARD ABSOLUTE ZERO

how the lowest temperatures are obtained

Temperature has a great effect on what man does, and how he does it. On a crisp autumn day a man can throw himself into his work and accomplish even more than he thought he could. The same man, during a midsummer heat wave, may languidly push himself home after a day's work, reach for a beer, wipe the perspiration from his face and wonder why he ever went to the office that morning.

Man is not alone when it comes to being affected by temperatures. The behavior of matter at very low temperatures, for example, can vary greatly from its behavior at ordinary temperatures. The properties that vary are not only thermal or thermodynamic, such as thermal conductivity, specific heat, or entropy; the electrical properties of matter also change. The prime example is conductivity, which in certain cases may become infinite (the phenomenon of superconductivity). To measure these properties of matter at low temperatures, it is essential to have: (1) a means of refrigerating the substances to temperatures feasible for experimentation; (2) a way of varying these temperatures; and above all (3) a method of measuring them.

The experimental techniques involved do not present any excessively difficult problems until the attempt is made to reach temperatures within a few degrees of absolute zero (−273.16° C or −459.69° F). When the goal is below 1° K (absolute), the difficulties become enormous and call for a complete change in experimental technique. Actually, the lowest temperature obtainable by the so-called ordinary methods is 1° K; this limit is imposed by the fact that liquid helium has the property of reaching temperatures close to this value when made to evaporate under certain conditions. Since liquid helium at ordinary pressures does not solidify at absolute zero, the technique used to obtain the extremely low temperature of 1° K consists of liquefying helium and causing it to evaporate quickly by pumping. The pumping must be quite rapid to ensure that no gaseous helium remains above the liquid helium, for the presence of the gas would promote the condensation rather than the evaporation of the liquid. The liquid helium will then reach a temperature of 1° K or slightly less.

This temperature is the starting point for the magnetic method, which allows

1

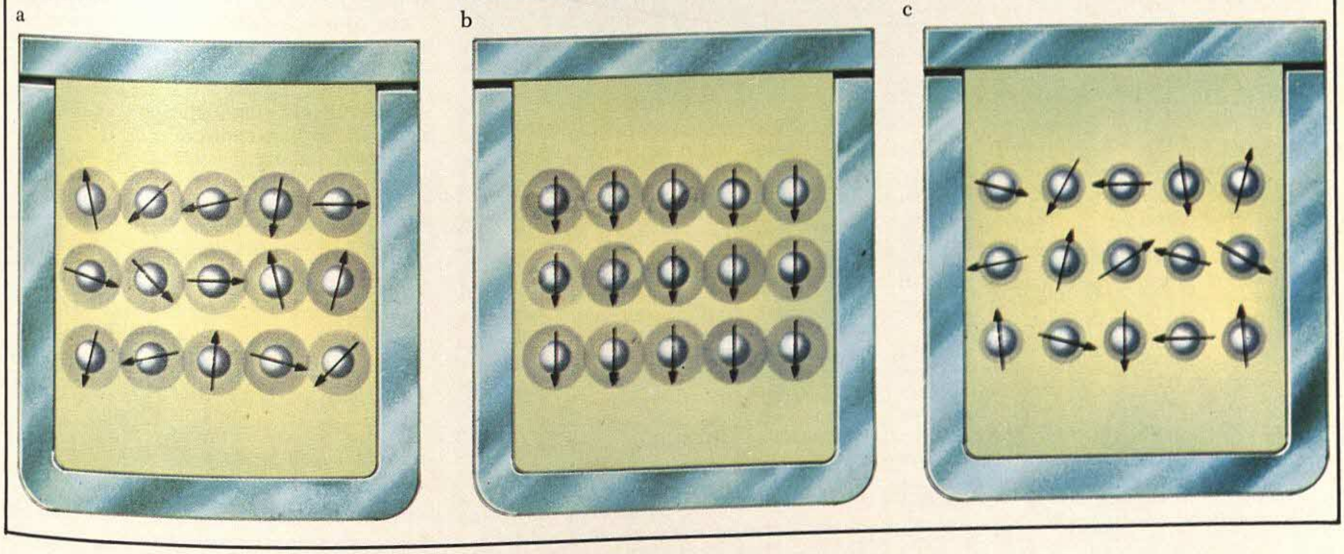
THE METHOD OF ADIABATIC DEMAGNETIZATION—Illustration 1a represents a block of matter enlarged to the point where the individual atoms become visible. The atoms are represented by small spheres, each surrounded by a halo; the width of the halo indicates the intensity of the thermal agitation of the atoms. This agitation should be imagined as corresponding to a temperature of 1° K. The paramagnetic substance is imagined as being immersed in a bath of liquid helium from which the liquid is gradually made to evaporate without causing the remainder to freeze. The arrows indicate the orientation of the magnetic moment of each atom. As can be seen from the arrows, the magnetic moments of the atoms at this stage are oriented at random.

If a magnetic field is now made to act on the substance, the magnetic moments of the atoms become oriented in the same direction (shown in Illustration 1b by the arrows, which are all parallel). This operation generates heat because a certain amount of work must be performed to reorient the magnetic moments of the atoms. Nevertheless, since the specimen is immersed in an isothermal environment refrigerated by liquid helium, its temperature does not rise. In short, magnetization takes place under isothermal conditions; and this is why the halos surrounding the atoms are shown with the same width as before.

Illustration 1c shows the third phase of adiabatic demagnetization. First, the thermal contact of the specimen with the liquid helium is eliminated. Then, the magnetic field is suddenly removed and the specimen becomes demagnetized.

The magnetic moments of the atoms again become oriented at random. In doing so they absorb energy from the specimen, and the thermal movements of the atoms are reduced. This leads to a fall in the temperature of the crystal of paramagnetic substance. The illustration shows the atoms not only with their magnetic moments again distributed at random, but also with halos that correspond to the strongly reduced thermal agitation.

After the demagnetization, it is desirable that the specimen remain thermally insulated from the environment as long as possible so that the specimen will not become heated by means of thermal radiation and conduction, and will remain ready for use.



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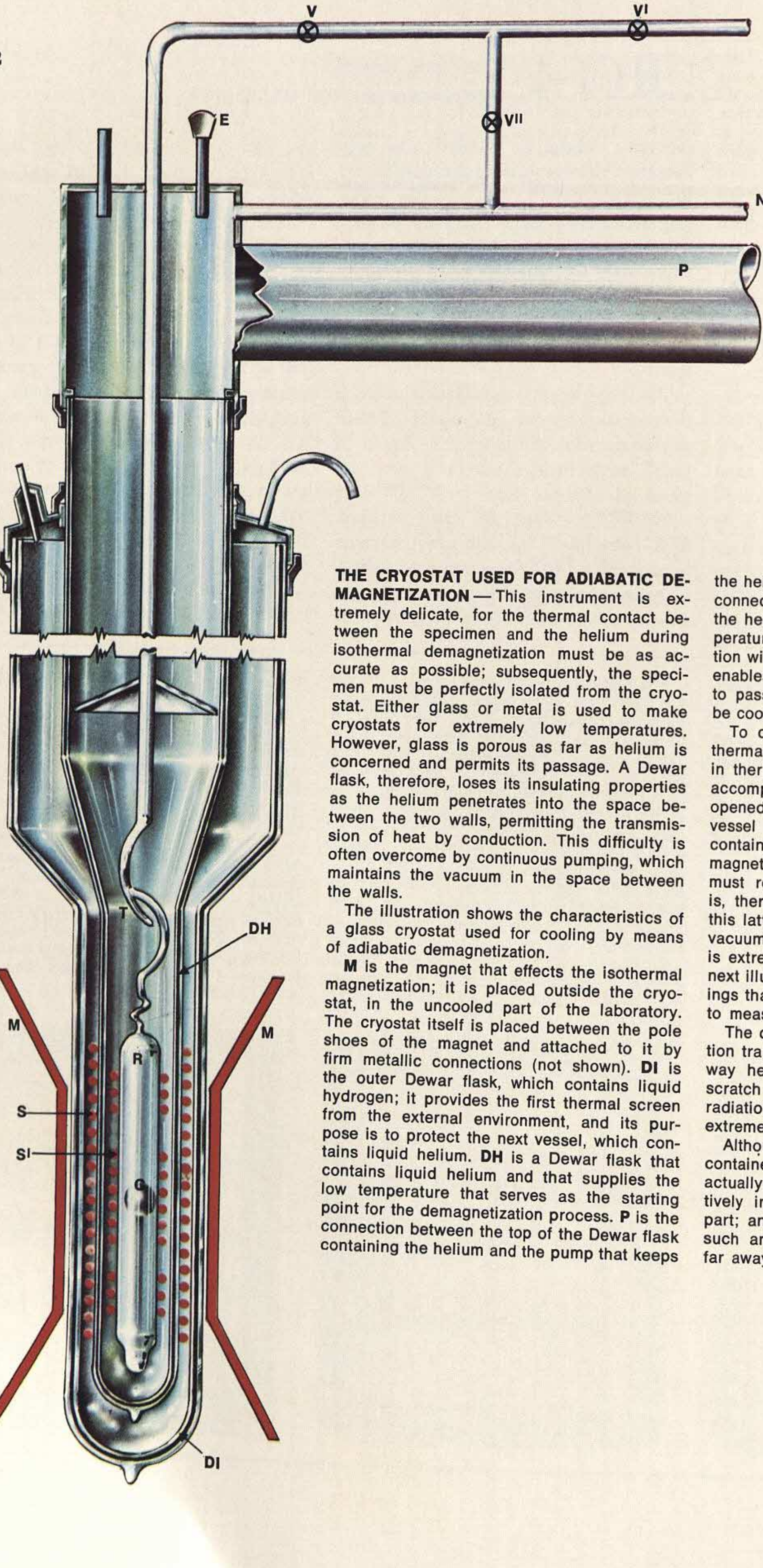

THE CRYOSTAT USED FOR ADIABATIC DEMAGNETIZATION — This instrument is extremely delicate, for the thermal contact between the specimen and the helium during isothermal demagnetization must be as accurate as possible; subsequently, the specimen must be perfectly isolated from the cryostat. Either glass or metal is used to make cryostats for extremely low temperatures. However, glass is porous as far as helium is concerned and permits its passage. A Dewar flask, therefore, loses its insulating properties as the helium penetrates into the space between the two walls, permitting the transmission of heat by conduction. This difficulty is often overcome by continuous pumping, which maintains the vacuum in the space between the walls.

The illustration shows the characteristics of a glass cryostat used for cooling by means of adiabatic demagnetization.

M is the magnet that effects the isothermal magnetization; it is placed outside the cryostat, in the uncooled part of the laboratory. The cryostat itself is placed between the pole shoes of the magnet and attached to it by firm metallic connections (not shown). **DI** is the outer Dewar flask, which contains liquid hydrogen; it provides the first thermal screen from the external environment, and its purpose is to protect the next vessel, which contains liquid helium. **DH** is a Dewar flask that contains liquid helium and that supplies the low temperature that serves as the starting point for the demagnetization process. **P** is the connection between the top of the Dewar flask containing the helium and the pump that keeps the helium in continuous evaporation. **N** is the connection to the manometer that measures the helium's pressure and, indirectly, its temperature. **V, V′** and **V″** are valves whose function will be explained later. **E** is a conduit that enables the wires of the electric thermometer to pass into the flask. **C** is the specimen to be cooled, and **R** is the vessel that contains it.

To carry out the magnetization under isothermal conditions, the specimen is placed in thermal contact with the liquid helium. To accomplish this, the valves **V** and **V″** are opened; the helium vapor coming from the vessel **DH** can thus pass into the recipient containing the specimen. Later, when the demagnetization is carried out, the specimen must remain completely insulated. Valve **V″** is, therefore, closed and valve **V′** is opened; this latter valve connects the vessel **R** to the vacuum pump. The structure of the vessel **R** is extremely complex and is examined in the next illustration. **S** and **S′** are conductor windings that establish the magnetic fields needed to measure the temperature of the specimen.

The curved tubing indicated by **T** is a radiation trap. Actually, radiation is about the only way heat may reach the specimen; a tiny scratch in the silvering that protects against radiation is quite sufficient to prevent reaching extremely low temperatures.

Although in the illustration the specimen container appears to be rather long, it is actually much longer because it must effectively insulate the warm part from the cold part; and one of the essential conditions for such an insulation is that the two parts be far away from each other.

even lower temperatures to be reached.

ADIABATIC DEMAGNETIZATION

To obtain temperatures below 1° K, thermal insulation must be provided for the specimen to be cooled. This thermal insulation is extremely difficult to achieve. Usually the substance is placed in a vessel from which all the air has been evacuated. The vessel itself has double walls, silvered on the inside; the space between the walls also is completely evacuated (principle of the vacuum bottle). This vessel is immersed in another that contains liquid helium cooled by the pumping method described above. Thus, not only is the desired thermal insulation achieved, but there is the added advantage of dissipating in the liquid helium any heat that may be liberated from the substance while it is cooling.

The method of cooling that achieves lower temperatures than that of helium in rapid evaporation consists of alternately magnetizing and demagnetizing a paramagnetic substance. When a paramagnetic substance is magnetized, its atoms are forced to assume a particular orientation, all in the same direction and sense; this implies that a certain amount of work is performed on the atoms. As a result, the temperature of the substance will increase, for the movements of thermal agitation (which occur at all temperatures, except theoretically at absolute zero) increase in intensity. The technique of cooling to very low temperatures with the method of adiabatic demagnetization consists of subtracting this excess heat from the paramagnetic substance to be cooled—while the magnetic field is still acting. The substance obtained in this manner has the same temperature it had at the beginning of the process, except that it is now magnetized. If the magnetic field is now removed, the substance becomes demagnetized and the atoms lose the characteristic of being oriented in the same direction. The energy needed to bring disorder back into the crystal is obtained from the thermal agitation energy of the atoms of the paramagnetic substance; consequently, the temperature of the substance falls still further. Many substances can be cooled by adiabatic demagnetization. However, since the lowest temperatures that can be reached depend on the magnetic properties of each specific substance, obviously every substance will not be capable of reaching the temperatures required for certain experiments.

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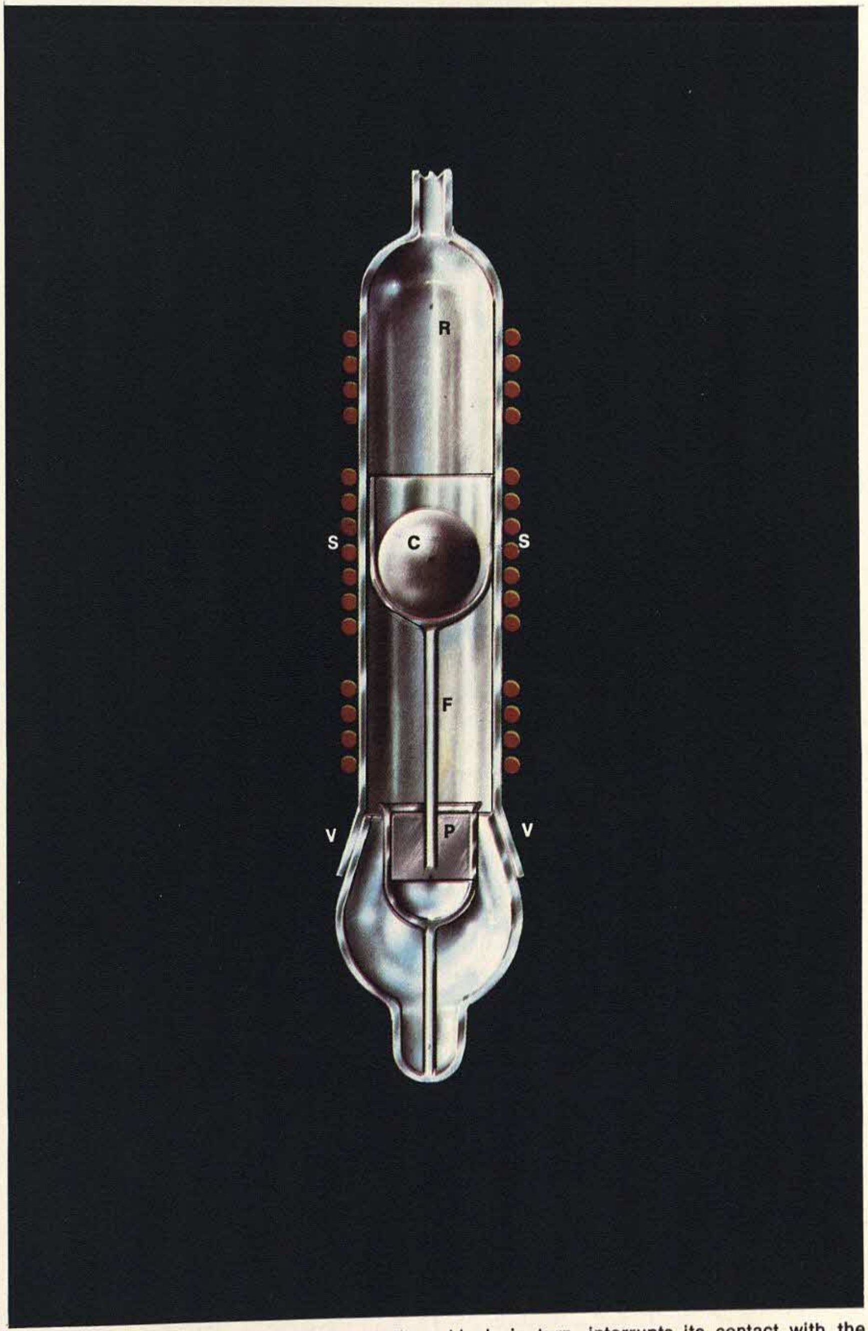

THE SPECIMEN CONTAINER—Each of the comparatively few low temperature research laboratories uses a particular type of specimen container for adiabatic demagnetization. The one shown here is made of glass that can be fused without the need to produce excessively high temperatures; such temperatures would be dangerous because most of the paramagnetic substances used are very delicate and can decompose when the temperature reaches a few tens of degrees. **R** is the glass vessel within which the specimen is placed; **S** indicates the conductor windings that produce the magnetic fields needed for the measurements. The specimen **C** consists of a small sphere of solid substance that rests on a small glass cup.

The stem **F** of the cup is extremely thin; in order to avoid even the small amount of heat it could conduct away, the stem is interrupted by a block of paramagnetic material **P.** This block, in turn, interrupts its contact with the vessel when it is subject to adiabatic demagnetization. A conic friction joint **V** with accurately ground surfaces enables the apparatus to be rapidly assembled and dismantled. This joint is made with great precision, for it must be capable of holding the vacuum when the helium is pumped out of the vessel.

The solenoids surrounding the vessel are used to measure those magnetic magnitudes that characterize the low temperatures produced. Three parameters are suitable for the measurement of the temperatures: (1) the magnetic susceptibility; (2) the coefficient of thermal absorption of the energy produced by an alternating magnetic field; and (3) the residual magnetic moment; that is, the magnetic moment that remains in the specimen even after the magnetizing action of the external field has been removed.

MAGNETIC PHENOMENA

from the natural magnet to the betatron

No one knows when magnetism was discovered, but the Greeks knew of it several centuries before the birth of Christ. Thales of Miletus (640–546? B.C.), one of the Seven Wise Men of ancient Greek philosophy, mentioned a natural magnet, a special kind of rock that had the extraordinary property of either attracting or repelling other pieces of the same rock. This mineral lodestone (a magnetic oxide of iron, magnetite, Fe_3O_4) was found near Magnesia, a city in Thessaly settled by the Magnetes—hence the name "magnet."

Early in the Christian era the Chinese discovered that a piece of iron rubbed against a lump of natural magnetic rock took on the same magnetic properties. At about the same time it was also discovered that magnets, suspended so they could rotate freely, have a second property of taking up a set orientation with respect to what are now known as the points of the compass. The modern ship's compass is an improved version of the same invention, but operating on the same principle.

Until the beginning of the nineteenth century, magnetic phenomena were considered to be in a class of their own, and apparently no one imagined that there could be any connection between them and the phenomena of electricity, which had been discovered earlier.

In 1820 the Danish physicist Hans Christian Oersted discovered that a conductor with an electric current passing through it produced a force field with the power of deviating a compass needle. This was the first known time that anyone had reason to suspect a relation between magnetic and electric phenomena. Within a few years a number of other important discoveries had shown that this relation was even closer than had been suspected and that electric current could be produced from the movement of magnets.

Although the relation between magnetism and electricity had now been demonstrated in a number of famous experiments, no one had yet explained the origin of magnetism in solids, including natural substances such as magnetite. Shortly after Oersted published the results of his experiments, the French physicist André Marie Ampère suggested that permanent magnetism in solids was caused by the movement of electric charges within them.

Ampère showed in 1825 that electric current in a circuit is equivalent to a magnetic shell of calculable strength. The right path toward the interpretation of the phenomenon had been found, but it was not until the 1930s that a complete theory could be worked out, since until that time, there had been no theory of the movement of subatomic particles in atoms.

Armed with such a theory, physicists

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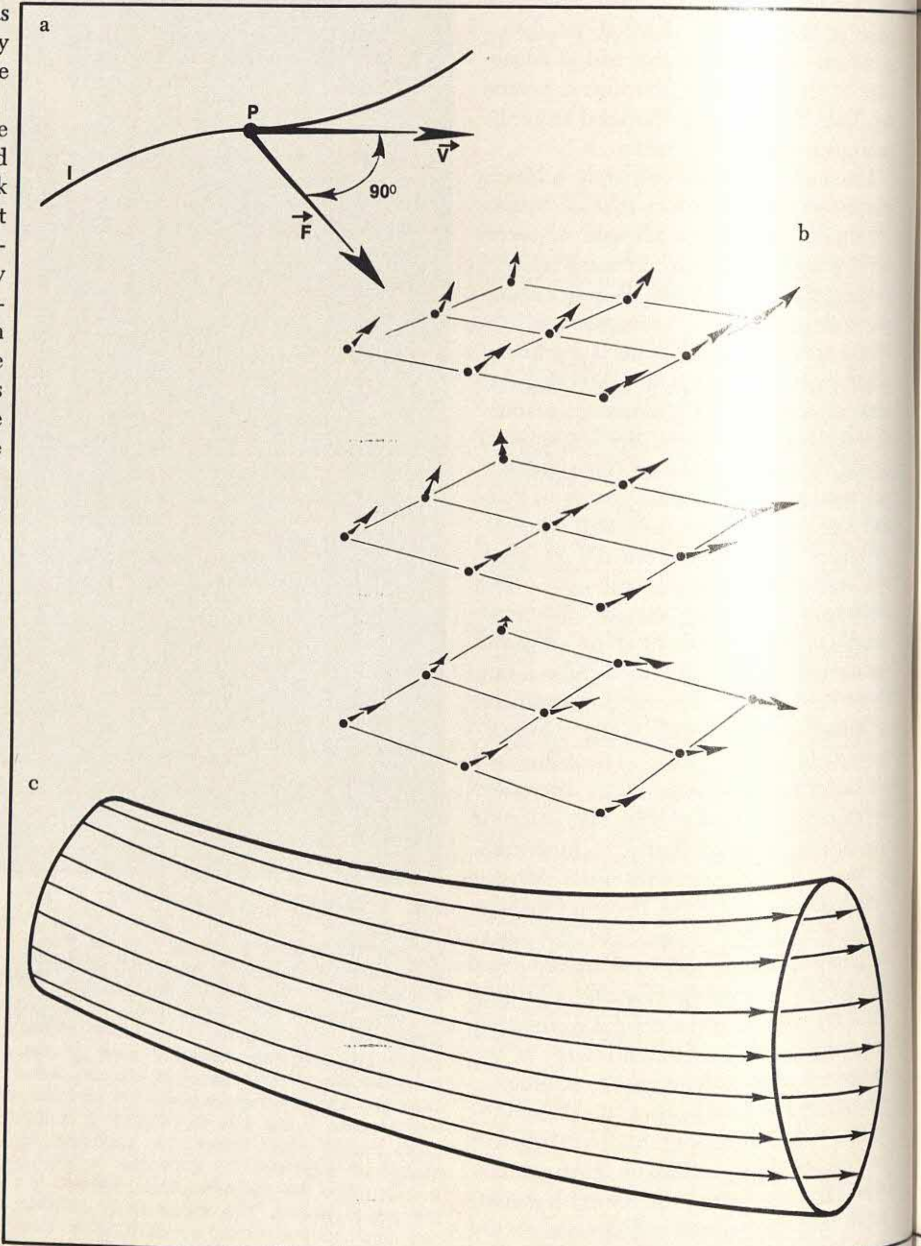

were in a position to work out the theory of many phenomena concerning the magnetic behavior of matter. An understanding of such complicated subjects requires study of two simple cases of the magnetic behavior of matter: an electric charge in motion inside a magnetic field and the magnetic field produced by an electric charge in motion. (In either case it is assumed that the medium in which the motion takes place and in which the magnetic forces operate is a vacuum, because this assumption facilitates interpretation, study, and observation of all the reciprocal actions.)

A convenient point at which to begin the study of these phenomena is that of the reaction between magnetic fields and electric charges in motion.

REPRESENTING MAGNETIC FIELDS—If an electric charge is at rest at a point in space where there are both electric and magnetic fields, the stationary charge is subject only to electrostatic forces. If, however, the same charge is caused to pass through that point at a certain velocity, it is found to be subject to a magnetic force as well as to electrostatic forces. The relationship between a magnetic force and the force it exerts on a moving electric charge is one of the simplest ways of defining a magnetic field. In Illustration 1a, a particle in motion along the path **l** at a velocity **V** is subject to a force **F** (which, as the illustration shows, is perpendicular to the velocity of the particle at that point) when it passes through the point **P**. This fact indicates the presence of a magnetic field if it is known that no electric fields are present in the same area of space. If any electric fields were present, the force acting on the particle as a result of its motion in the magnetic field would be added to any other forces produced by the electrostatic field.

This property of a magnetic field, based on a simple experimental observation, shows that it is convenient to represent the magnetic field in such a way that it is possible to calculate the force that is exerted on a charged particle of known velocity. The magnetic field may be represented by a vector, an entity represented geometrically by an arrow. This vector is denoted by **B** and is called the magnetic induction.

Illustration 1b shows a network of points in space, each with an arrow showing the intensity of the magnetic induction at that point—one of the ways in which a magnetic field can be represented.

Another way is to draw, for the area of space concerned, the flux lines of the induction; that is, the lines drawn in such a way that the induction vector is always tangent to the line itself. Illustration 1c shows how this representation is achieved: Where the lines of force are close together, the induction intensity is greatest. The passage of a charged particle through a point at which the flux lines are close together involves the exertion of a stronger force than if the charged particle were to pass at a point where the lines are more widely spaced (provided that the angle between the path of the particle and the direction of the magnetic induction is equal).

2

THE FORCE EXERTED ON A CHARGE IN MOTION—Illustration 2a shows how it is possible to calculate the forces exerted on a charge in motion through a magnetic field. A particle with the charge **q** (assumed positive), in motion on a path **l**, reaches a point **P** at which it is subject to the magnetic induction represented by the vector **B**. The result is that the particle is driven upward by the force **F**. The calculation of the force exerted on the charge **q** is simplified if the velocity and the magnetic induction at **P** are perpendicular to each other; that is, if the angle **BPV** is a right angle. Then, the magnitude of the force $\mathbf{F} = \mathbf{qVB}$.

The relative direction of the vectors involved in this formula for the action of magnetic fields on particles in motion can be remembered by the left-hand rule (Illustration 2b). If the velocity vector is in the direction of the middle finger and the magnetic induction vector along the forefinger, the force will be exerted in the direction of the thumb. This rule is useful for understanding immediately without risk of error the direction of the force exerted on a particle in motion.

When the velocity **V** and induction **B** of the particle are at an angle of less than 90°, it is sufficient to consider the component of the velocity that is perpendicular to the induction. The value of this component is $\mathbf{V} \sin \phi$, where ϕ is the angle between the velocity and the induction. The previous formula becomes $\mathbf{F} = \mathbf{qVB} \sin \phi$. By using the symbols adopted in vector calculations this formula can be written $\mathbf{F} = \mathbf{q}\,\mathbf{V}\mathbf{x}\mathbf{B}$, when **x** is the symbol of the vectorial product of two vectors and **V**, **B**, and **F** are vectorial magnitudes.

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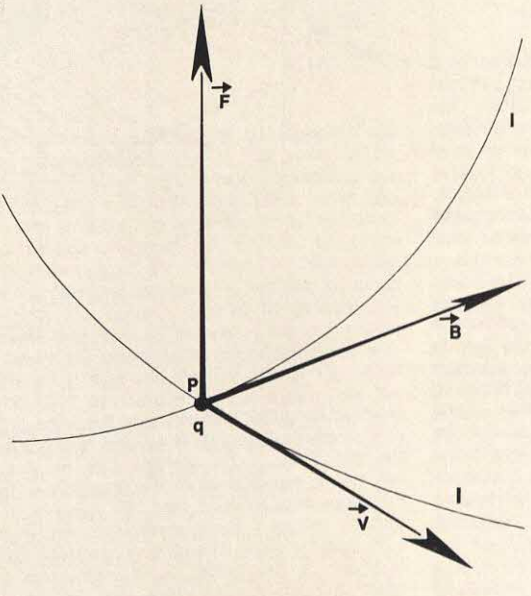

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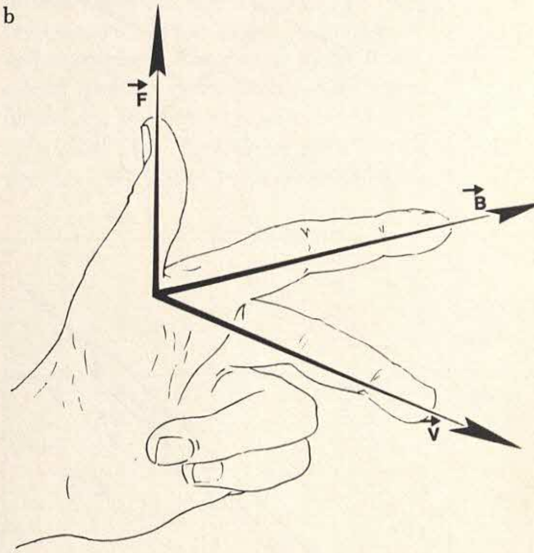

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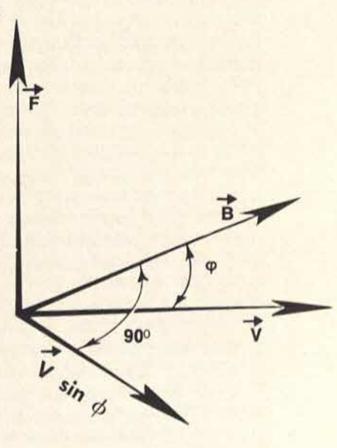

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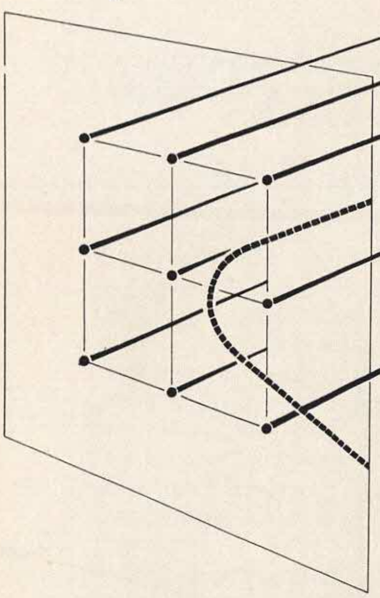

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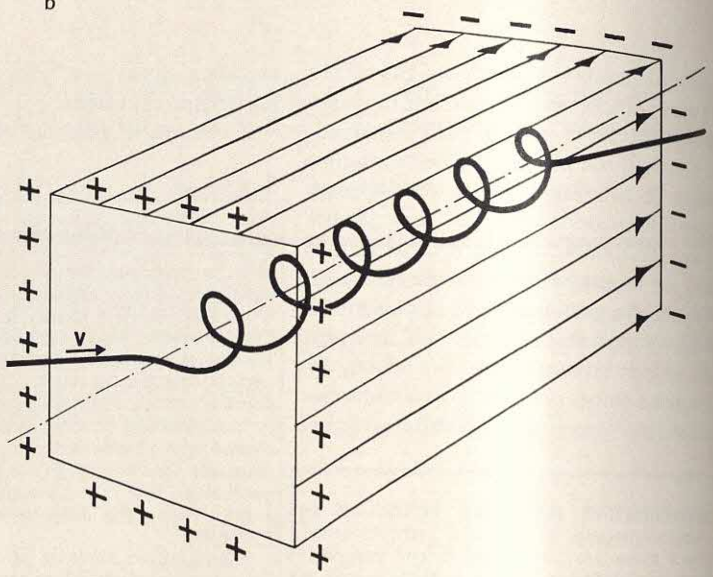

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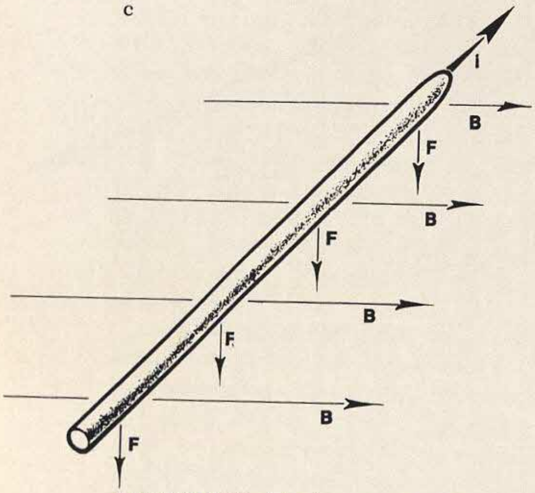

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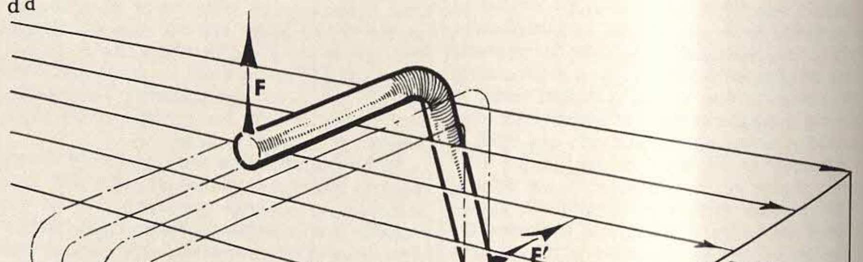

APPLICATIONS—The law of the action of a magnetic field on electrostatic charges in motion has a large number of applications. The law makes it possible to interpret certain phenomena concerned with the action of magnetic fields on electric charges, and to construct a large number of electric and electronic instruments. The law is also of fundamental interest in electrical engineering because electric motors are based on an application of it.

Illustration 3a shows a number of induction vectors, each parallel to one another and each of the same intensity. If a charged particle is sent into this field perpendicularly to the direction in which the arrows of the induction vectors are pointing, the particle will move on a circular path whose radius depends on the charge and velocity of the particle and on the intensity of the magnetic field. Because the force is exerted perpendicularly to the direction of the velocity of the particle, the magnitude of the velocity does not vary, although its direction does; hence, the path of the particle is a circle. This is the case in a particle accelerator in which the motion of the charges is calculated by using the law of the action of a magnetic field on electrostatic charges.

A more complicated case of the action of a magnetic field on the motion of a particle (Illustration 3b) is that in which the particle is subject to acceleration produced by an electrostatic field, and moves at the same time in a magnetic field that is parallel to the electrostatic field. If the particle has an initial velocity **V,** not parallel to the direction of the magnetic and electric field, the path of the particle will be a helix whose pitch increases.

A single moving charge in a magnetic field is shown in Illustration 2a. If there were instead a number of positive charges moving along a conductor, the charges in this case would be subject to a force driving them downward as shown in Illustration 3c.

An important example of reciprocal action between electric currents and magnetic fields is that of a coil conductor (Illustration 3d). A current **i** is passing through the coil in the direction shown by the arrow. The coil has been placed at an angle to the magnetic field. On the sides of the coil are vectors indicating the forces to which each side of the conductor is subject. The resultant of the forces **F, F′, F″,** and **F‴** is a torque tending to straighten the conductor and make it take up the position shown by the broken lines. This torque is caused only by the forces **F** and **F‴** because **F′** and **F″** cancel one another.

This is the principle on which an electric motor is based—a coil conductor is set in a magnetic field and an electric current passed through it; the interaction of the magnetic field and the moving charges of the current causes the coil to rotate.

THE MAGNETIC FIELD PRODUCED BY ELECTRIC CURRENTS

Oersted's experiments

There are times when rules from the past have to be, if not broken, at least somewhat modified. One axiom states that apples and oranges cannot be added together. Another states that electric and magnetic fields should be studied separately because they are apparently very different in nature. However, perhaps the rule needs a little bending here, for the two fields are quite closely connected. They are more like adjoining states in the same region of the country than different nations or continents; and so combined study can yield large dividends.

Combined study of electric and magnetic fields will show, for example, that (1) the movement of an electric charge generates a magnetic field; and (2) certain laws relate the properties of the magnetic field to the motion of the charge. Furthermore, by using these laws it is possible to predict the magnetic behavior of matter; this is true in regard to individual atoms as well as solid substances, which consist of many atoms grouped together.

Only an electric charge in motion is capable of inducing a magnetic field. In fact, an electric charge at rest can exercise only electric forces on the charges in the space surrounding it; the laws that govern these forces are the ordinary laws of electrostatics. When the charge that produces an electric field is in motion, it will supplement the electric forces it exercises over its surroundings with other forces of a magnetic nature.

In 1820 the Danish physicist and chemist Hans Christian Oersted observed

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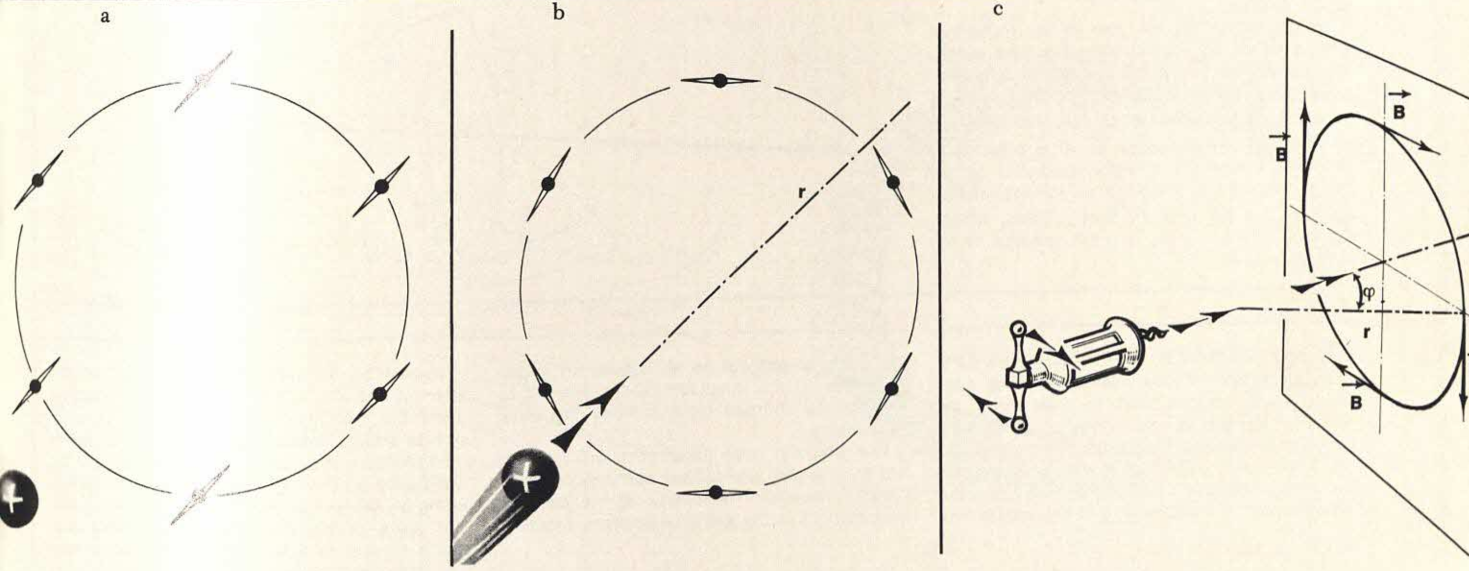


THE FIELD PRODUCED BY A CHARGE IN MOTION—An electric charge at rest does not produce any magnetic effects around itself. If a compass with a highly sensitive magnetic needle is placed close to it, as Illustration 1a shows, the needle will assume a position dictated by the Earth's magnetic field. Moreover, this position will be completely independent of the relative positions of the compass and the electric charge. The illustration shows that no matter how the compass is placed with respect to the charge, the needle always will assume a position parallel to the magnetic field of the Earth; it will not be influenced in any way by the electric charge.

What happens when the electric charge, no longer at rest, is in motion? In Illustration 1b, the direction of the motion is indicated by the arrow on the broken line **r**. Now the compass placed close to the electric charge in motion will be subject not only to the Earth's magnetic field, but also to a field set up by the motion of the charge. What happens when the magnetic action due to the motion of the charges is much greater in proportion to that of the Earth's magnetic field? Also, what happens if suitable measures are taken to cancel the Earth's magnetic field in the immediate neighborhood of the needle? In both cases, as the compass is placed in various positions around the electric charge in motion, the needle will react as shown in the illustration.

From the Oersted-like experiment just performed, a map (Illustration 1c) of the magnetic field can be deduced; it shows how the magnetic induction vector $\vec{\mathbf{B}}$ is arranged in a plane perpendicular to that of the motion of the electric charge. The vectors that represent the magnetic induction (shown by the arrows) are arranged in the same manner as a corkscrew would have to be turned in order to make it move forward in the direction of the motion of the electric charge causing the magnetic field. This is generally called the corkscrew rule. It shows the relative directions of both the charge and the induction vector.

If the equation of the motion of the pointlike particle carrying a given electric charge is known, it is possible to calculate the intensity of the magnetic induction vector at the various points of the field: it is found that this is proportional to the quantity of electric charge that travels a unit distance (1 cm) in a unit of time and also to the sine function of the angle ϕ shown in the illustration. In other words, the intensity of the induction becomes greater as the element of the trajectory traveled by the charge approaches the plane in which the induction is calculated. Also, it is inversely proportional to the square of the distance **r** that separates the charge in motion from the point at which the intensity of the magnetic induction vector is being calculated. This law is generally known as the Biot-Savart Law.

that a magnetic needle, when brought near a conductor carrying an electric current, deflects from the position it normally assumes because of the Earth's magnetic field. From this basic experiment the laws of the magnetic field can be deduced. Careful probing will disclose that magnetic fields can be produced by electric charges in motion and, therefore, by conductors carrying an electric current. Because of the importance of his discovery, Oersted was widely honored.

Oersted's experiment and its interpretation provide the key to understanding magnetic fields produced by currents. The experiment can be described by means of the magnetic induction vector $\vec{B}$. Exactly what this vector represents becomes clear when it is compared with the intensity vector of the magnetic field. In the following considerations, the induction vector represents the magnitude that is ordinarily associated with a magnetic field.

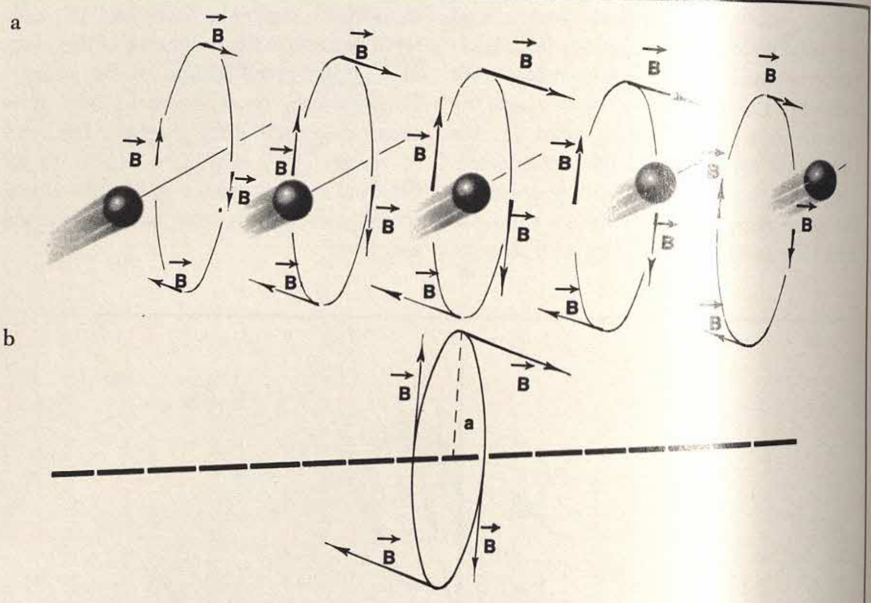
2

THE BIOT-SAVART LAW—Once the two previous illustrations are understood, it is easy (1) to see that a conductor carrying an electric current produces a magnetic field, and (2) to calculate the intensity of this field in the case of a straight conductor.

Illustration 2a shows the pieces into which the conductor may be imagined to have been subdivided and the magnetic field produced by each division. The intensity of the magnetic induction vector $\vec{B}$, when evaluated in accordance with the criteria shown under Illustration 1, is numerically different in the various cases; however, it is always in the same direction.

In Illustration 2b, the sum of the induction effects of all the circuit elements into which the conductor has been divided is a single intense induction vector $\vec{B}$.

It is possible to establish that the intensity of the magnetic induction $\vec{B}$, at a point at a distance **a** from the straight conductor carrying a current **i** and having an infinite length, is given by the formula $\vec{B} = \mu_0 i / 2\pi a$, where μ_0 is a constant. This is often referred to as Ampere's law.



3

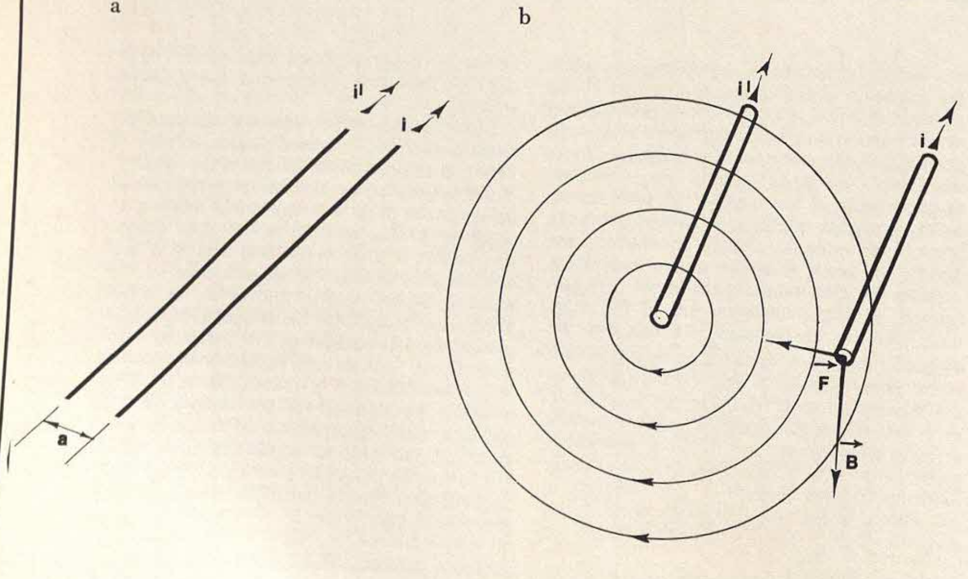
FORCES BETWEEN CURRENT-CARRYING CONDUCTORS—If two current-carrying conductors are brought close to each other, directional forces are exercised between the two conductors. In fact, both the conductors produce magnetic fields in accordance with the laws already illustrated; the electric charges in motion along one of the conductors will become subject to attractions or repulsions due to the magnetic field produced by the electric charges moving along the other conductor.

The simplest case (Illustration 3a) has two straight, parallel conductors carrying currents. **i** and **i′** represent intensities of the currents they carry; **a** is the distance between them.

Illustration 3b shows a section across the two conductors. In the plane of the section are induction lines arranged in the form of circles around the conductor on the left (similar induction lines could be shown around the conductor on the right). The charge in motion along an element of the conductor that crosses the plane of the section will, therefore, become subject to a force whose direction may be found by means of the right-hand rule. When applied to this case, the rule makes it possible to prove that the force acts in the direction shown—toward the other conductor.

The Biot-Savart Law also makes it possible to calculate the intensity of the force exercised between two conductor elements of unit length: $F = \mu_0 i i' / 2\pi a$. This force is proportional to the product of the intensities of the currents **i** and **i′** carried by the two conductors, and inversely proportional to the distance **a** separating them. The force is one of attraction when the two currents flow in the same direction, and repulsion when they flow in opposite directions.

This result can actually be used to define the unit of current intensity. An ampere can be defined as that intensity of current flowing in two straight, parallel conductors of infinite length that will produce an attractive force of 2×10^{-7} newtons for every meter of wire. Only mechanical, not electrical, magnitudes are involved in this definition. These include the distance between the two conductors and the force that is created. The ampere defined in this manner is called the absolute ampere, because its definition is not based on electrical magnitudes and is independent of them.



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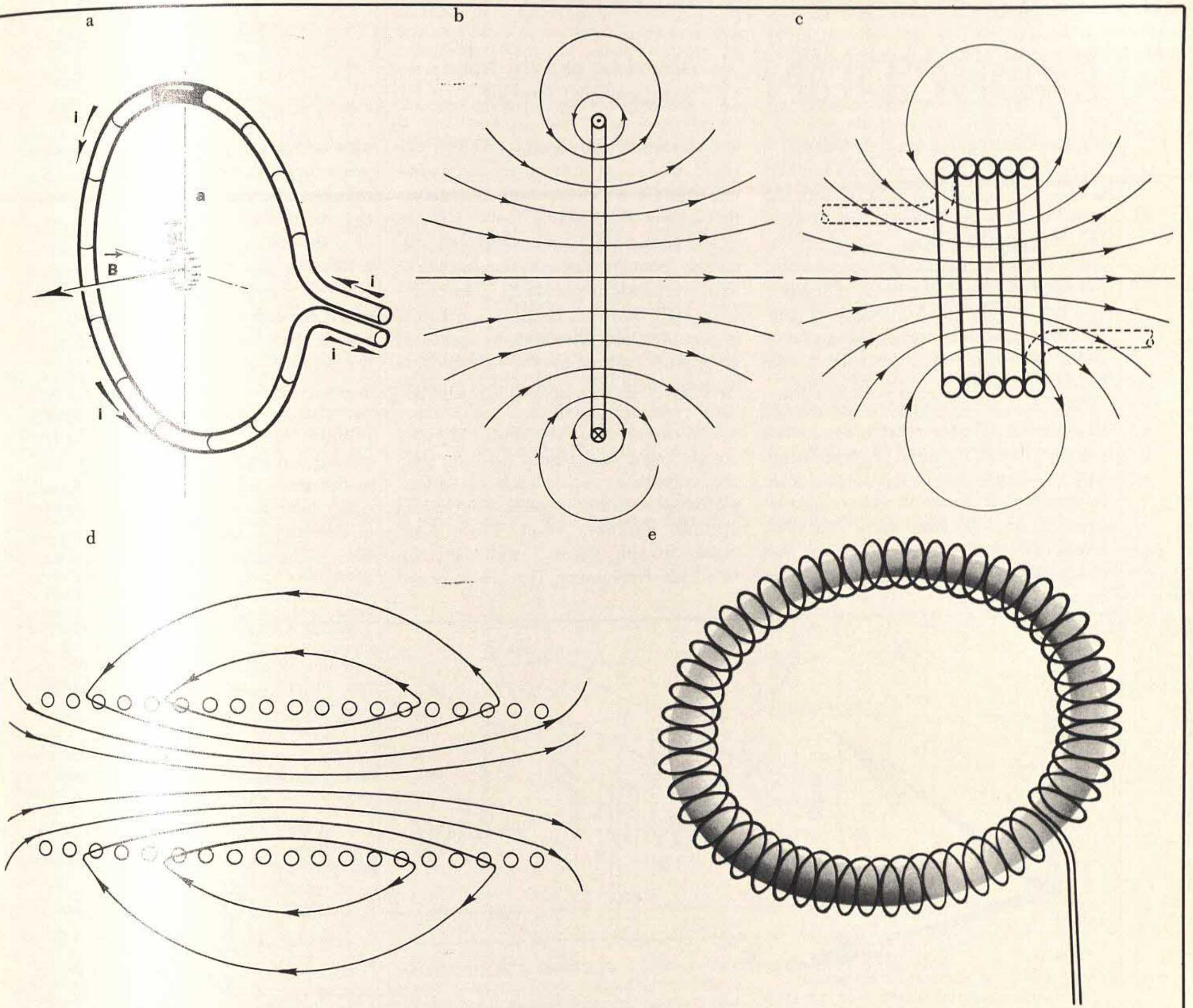

COILS, SOLENOIDS, AND TOROIDS—Experience garnered from working the previous experiments is employed in the examination of what happens in proximity to any conductor when a current flows through it. A good approach to this problem is to consider the simplest form of conductor, the circular coil.

If a circular coil (Illustration 4a) has a radius of **a** and the current flow of intensity is **i**, what will be the intensity of the induction in the surrounding space, at the center of the coil, for example? For this problem, the coil may be thought of as being split into a large number of small segments, each short enough to allow it to be considered straight. Note the dark segment at the top of the coil; it may be considered as part of a straight conductor of infinite length. The problem is to calculate the intensity of the induction that the conductor generates at the center of the coil because of the current flowing through it. Actually, this is similar to the problem discussed under Illustration 2. The induction caused at the center of the coil is represented by the short vector $\vec{B'}$ shown a little above the center of the coil. All the other elements of current behave in the same manner, and each of them will cause a weak induction at the center of the coil. All these inductions can therefore be represented by parallel vectors and their sum is the vector $\vec{B}$ at the center of the coil. According to the Biot-Savart law, the intensity of the magnetic induction at the center of the coil can be shown to be $\vec{B} = \mu_0 i/2a$.

A slightly more complex calculation would make it possible to construct each point of this illustration showing the flow lines of the induction field through the section of the coil (Illustration 4b). In the immediate neighborhood of the coil conductor, all the flow lines close back on themselves to form rings; but those that pass close to the axis of the coil close back onto themselves at great distances, while the one that passes through the axis of the coil closes at infinity.

A number of coils placed in contact with each other, like a spring, form a solenoid (Illustration 4c). Here the induction field is produced by a solenoid of only five coils. It is quite similar to the field set up by the single coil in Illustration 4b.

The striking feature of the magnetic field produced by a long, current-carrying solenoid of many coils (Illustration 4d) is that the lines of force inside the solenoid are practically straight and parallel to its axis. This important property of the solenoid is utilized in many instruments, especially those used to magnetize compass needles with extreme precision and uniformity.

If a solenoid is bent in such a way that its axis, originally a straight line, comes to form a circle and the two ends of the solenoid are brought together, the result is a toroid (Illustration 4e). A key characteristic of the toroid is that the lines of the induction field close themselves within the toroid itself, not outside at infinity as in the case of the open solenoid. The field inside the toroid has a practically constant intensity, while on the outside hardly any field exists.

ELECTROMAGNETIC INDUCTION

electrical energy from mechanical energy

An electrical charge moving through a magnetic field is subjected to a force that is directly proportional to the charge and speed of the particle and the intensity of the magnetic induction vector of the field. The direction of this force—called the Lorentz force, after the Dutch physicist Hendrik Antoon Lorentz—is perpendicular to the direction of the magnetic induction vector and to the motion of the particle on which the force is acting.

This fact is utilized to move electric charges in conductors, that is, to produce electric current. It should be remembered that a conductor can be represented schematically as an array of positive ions located in fixed positions on a crystalline lattice—positions around which the ions can oscillate but which they cannot leave. The conductor also contains an electronic cloud, that is, an array of free electrons—mostly the outer electrons of the conductor's atoms—that usually move, because of thermal agitation, in a completely disorderly manner through the lattice of ions, with little impediment. These electrons may, however, be given a net drift in one particular direction, by means of an applied external electric field or by a magnetic field that exerts forces on electrical charges in motion.

The discovery of the laws that govern the action of magnetic fields on electric current was the work of several nineteenth-century physicists, including Michael Faraday, Franz Ernst Neumann, Joseph Henry, and Heinrich Friedrich Emil Lenz. The laws opened up a new era of technology by making it possible to produce electromotive force derived from mechanical energy rather than from chemical energy (such as that of a storage battery). This has resulted in the design of generators, alternators, and transformers, as well as instruments of the greatest importance in physical research, such as particle accelerators of the magnetic-induction type, and the so-called betatrons (which accelerate beta particles, or electrons). The functioning of these instruments is based on the simple laws of electromagnetic induction.

The study of the laws of electromagnetic induction is simplified by the use of illustrations showing the relative positions of the conductors and the magnetic fields.

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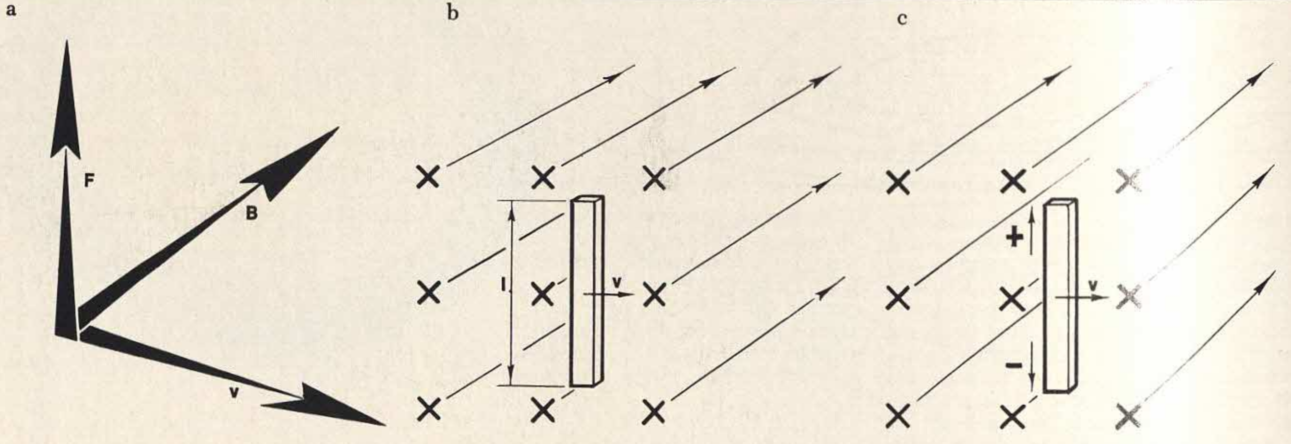

INDUCTION IN A MOVING CONDUCTOR—An electric charge moving in a direction perpendicular to the lines of induction of a magnetic field becomes subjected to a force that acts at right angles to the direction in which the charge is moving and the direction of the induction lines of the magnetic field.

In Illustration 1a, the arrow toward the right represents the direction in which a positive charge is moving at a velocity **v**; the arrow **B** at right angles to the rear represents the direction of the induction lines of the magnetic field; and the arrow **F** at right angles upward represents the direction of the force to which the charge is subjected.

Illustration 1b makes it possible to interpret what happens in a conductor of a length **l** moving within a field of uniform magnetic induction. The arrows indicate the direction of the lines of magnetic induction. The arrows are parallel with each other and away from the observer, and are perpendicular to the plane in which the conductor is moving; the crosses show the points of intersection of the lines of magnetic induction with the plane of the conductor. The conductor is moving, at a speed **v**, toward the right. What happens to the free electrons within the conductor, the electrons that move both because of thermal agitation and also because of the motion of the conductor of which they are part?

The thermal agitation of electrons has no effect on the Lorentz force, because the electrons move at random in all directions; whereas under the described conditions, each electron is subjected to a force that pushes it sideways, as shown in Illustration 1c. The positive charges are also shown moving to the top of the conductor, and the negative charges are shown at the bottom. This is, in fact, an abstraction, for the only motion is that of the negative charges, the electrons; their movement in one direction (downward) has the effect of a positive charge simultaneously moving in the other direction (upward), and therefore the ends of the conductor are polarized.

This polarization is brought about by a force known as the induced electromotive force, caused by the movement of the conductor in the magnetic field. Electromotive force only temporarily displaces the electrical charges from their original uniform distribution throughout the conductor so that they are finally concentrated at each end—a concentration that lasts only as long as the conductor moves in the magnetic field. As soon as the conductor stops moving, the concentrations are followed by the original situation in which the conductor is everywhere neutral.

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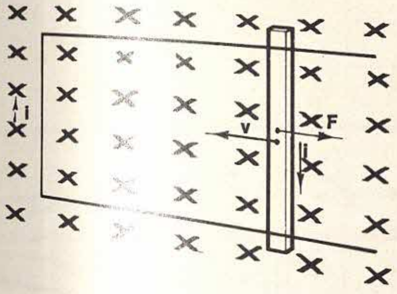


ELECTRICAL ENERGY DERIVED FROM MECHANICAL ENERGY

ELECTRICAL ENERGY DERIVED FROM MECHANICAL ENERGY—If the conductor in the previous drawing is assumed to be a parallelepiped that can easily slide along another conductor bent into the shape of a C, the two conductors can become in effect a circuit. It is further assumed that this circuit of conductors is placed within a magnetic field with its lines of magnetic induction directed, as before, away from the observer. In the circuit, the C-shaped section is fixed, and, therefore, is not subjected to an induced electromotive force. The mobile section moves toward the left, at a velocity **v**; therefore, its positive pole will be at the bottom and the current will flow in the direction indicated by the arrow **i**.

Now, although the C-shaped part of the circuit cannot move, and the force due to the magnetic field is not apparent here, the presence of the magnetic field is apparent in the moving part of the circuit. It is the motion of this part of the circuit through the magnetic field that induces the electromotive force that causes a current to flow, as shown, through the circuit. At the same time, the moving charges that constitute the current flowing exert a force **F** back on the mobile conductor. This force is in such a direction as to oppose the motion of the mobile section, so that in order to keep the section moving at velocity **v**, work must be performed against force **F**—work equivalent to the energy of the current flowing in the circuit. The positive charges moving in the direction of arrow **i** are subjected to forces that produce force **F**.

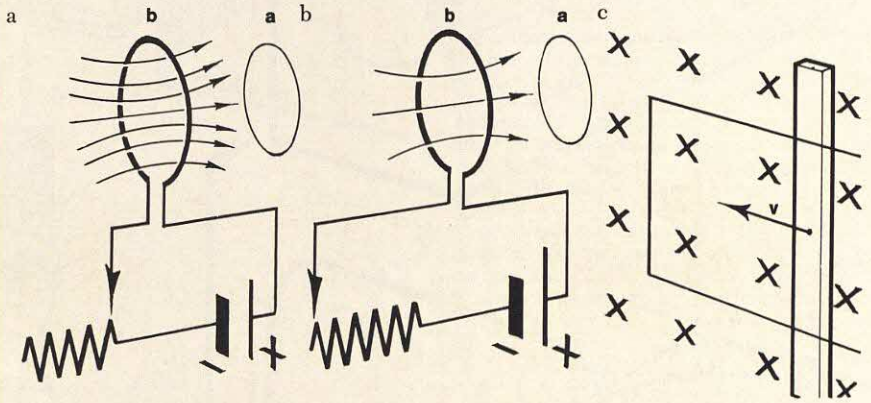
4

THE FARADAY-NEUMANN LAW—From a reexamination of Illustration 2, it can be stated that an electric current is induced in a circuit formed by a fixed and mobile conductor by the motion of the mobile section. The greater the speed of the motion of the mobile section, the more intense is the current induced in the circuit. There are many ways of varying the induction flux that passes through the loop of a conductor.

In Illustration 4a, by means of a variable resistance (bottom left) the current generated by the battery is allowed to flow through the loop **b;** because the resistance is almost entirely excluded, the current is rather intense, and it is shown producing many induction lines (with arrows), some of which cross the circular loop **a.** In Illustration 4b, the resistance is included in the circuit, reducing the current flowing through loop **b,** diminishing the intensity of the magnetic field, and, therefore, allowing fewer induction lines to penetrate loop **a.** In this case, the diminution of the magnetic induction flux through **a** is not caused by a displacement of the circuit, as in the previous case, but is caused electrically by a less intense circuit flowing through loop **b.** The effect, however, is the same: variation of the magnetic induction flux induces an electromotive force in loop **a,** and therefore a current flows in it.

For any given situation, the induced electromotive force can be calculated by means of the Faraday-Neumann law, which states that the force is equal to the time rate of change of the flux that passes through the circuit. Returning to Illustration 2, the variation of flux $(\Delta\phi)$ equals $-B\Delta A$; that is, $-Bl\Delta s$, where A represents the projection of the area of the circuit loop in a plane perpendicular to the lines of induction. $-\Delta A$ represents the diminution of A, l represents the length of the mobile conductor, and Δs represents the distance the mobile conductor covers in time Δt.

This relationship can be transformed into the form $\Delta\phi/\Delta t = -Blv$, by substituting $\Delta s = v\Delta t$, where Δt is the time in which the variation of the flux occurs, and v is the speed of displacement of the mobile section that produces the variation of the loop's area. Thus, in the present situation, the magnitude of the induced electromotive force **F** is given by Blv. The electromotive force is always such that its own effects act in opposition to the cause that has produced it. The electromotive force induced in the circuit shown in this illustration, for example, has been caused by the diminution of the electromagnetic induction flux; as the mobile arm moves toward the left, it generates a current in the circuit that tends to push the arm toward the right.



THE RIGHT-HAND RULE—The simple right-hand rule finds the direction of the current induced in a conductor moving in a magnetic field. The thumb, forefinger, and middle finger are pointed at right angles to each other, the thumb pointing in the direction in which the conductor moves **v**; the forefinger in the direction of induction of the magnetic field **B**; and the middle finger in the direction **i** in which the current is flowing.

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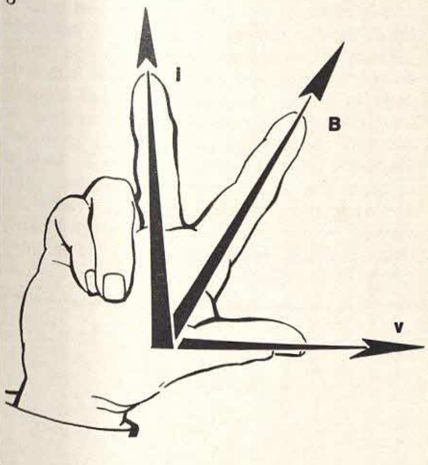


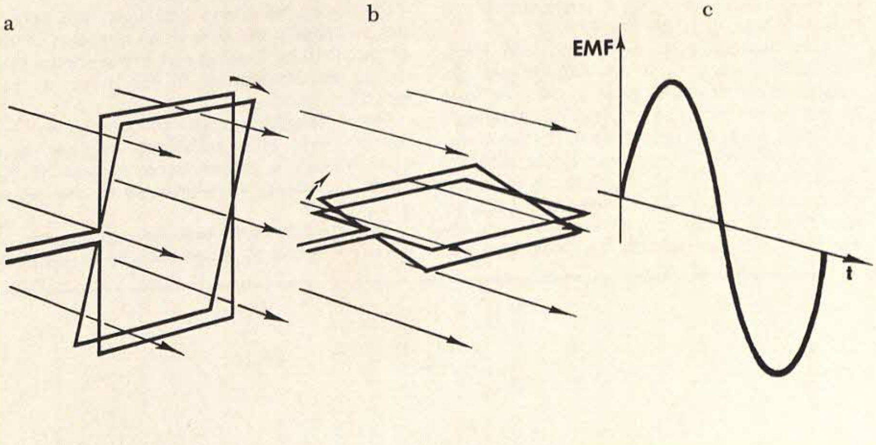
5

INDUCTION IN A ROTATING LOOP—A very important application of magnetic induction is found in the construction of alternating-current generators. The principle behind these consists of rotating a loop of conducting material in a magnetic field.

In Illustration 5a, the loop, rotating about a horizontal axis, is in a position perpendicular to the induction lines of the magnetic field. In this position the variation of the induction flux is small, and, therefore, the induced electromotive force is also small.

In Illustration 5b, the loop is in line with the magnetic field, and the induced electromagnetic force reaches a maximum.

By continuously rotating the loop between these positions, a sinusoidal variation of the induced electromagnetic force (emf) is obtained, as shown in Illustration 5c. An electromagnetic force that varies sinusoidally in time produces an alternating current flowing through the loop.



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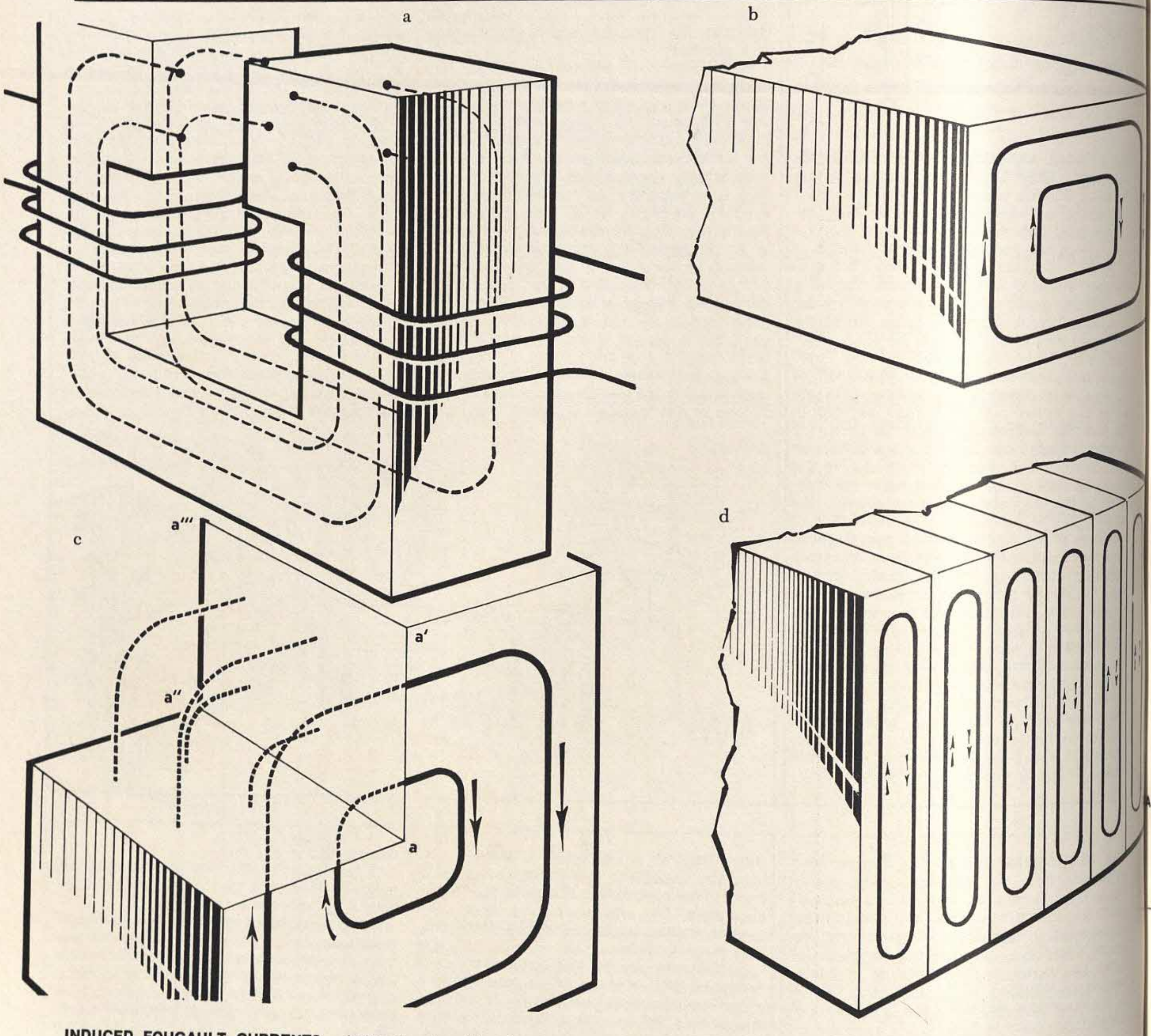

INDUCED FOUCAULT CURRENTS — Induced currents have many useful applications, but they also may have harmful effects.

In an alternating-current transformer (Illustration 6a), many turns of copper wire are wound around the core; through the wire flows an alternating current that generates a variable magnetic field along the axis of the turns. If the core were formed of a single block of metal, it would be subjected to an induction effect, and an induced electromagnetic force would begin to act on it because the core would be within a variable magnetic field produced by the alternating current.

Illustration 6b shows how induction generates currents in the core in the direction of the arrows, thereby wasting part of the energy that should be transferred to the turns of the secondary coil.

These induced currents (Illustration 6c) encounter very little resistance because they flow through a rather large section of the armature, marked in the diagram by the letters **a, a', a'', a'''**.

The intensity of the induced currents can be greatly reduced by a special type of armature construction. If the armature is constructed in the form of a number of plates insulated from each other, as shown in Illustration 6d, the induced currents are forced to flow within the plate in which they are generated, because their passage from one plate to another encounters considerable resistance; they will, therefore, lose much less energy. Induced currents that cause energy losses are known as Foucault currents because they were first studied by the French physicist Jean Bernard Léon Foucault, who also introduced improvements in the electric arc.

7

THE BRAKING ACTION OF FOUCAULT CURRENTS—Foucault currents, also called eddy currents, are used in some instruments and arrangements.

Illustration 7a represents the circuit of a galvanometer. It consists of a moving coil suspended in a magnetic field by a thin fiber of quartz or some easily twisted metal. The passage of a current through the moving coil produces a rotation of the coil that is opposed by the torsion of the fiber.

When the current stops flowing through the coil, the elasticity of the fiber to which the coil is attached will bring the coil back to its rest position. This will occur after a very long series of oscillations that can last for as much as ten minutes in some instruments. The oscillations can be stopped by connecting the two ends of the coil to form a closed circuit, in which the movement through the magnetic field induces a current. The magnetic field acting on the coil is manifested by a torque that stops the coil from rotating; the coil then returns to its rest position without further oscillation (Illustration 7b).

If a metal disk is made to rotate between the poles of a magnet, the magnet will induce currents in the disk; the currents flow more or less along the lines shown in Illustration 7c. The movement of these currents in the magnetic field in which the disk is located causes a force that drags the magnet and makes it rotate; or, the magnet can be rotated, thus dragging the disk and making it rotate. The dragging force is proportional to the intensity of the induced currents, and these are in turn proportional to the speed of rotation of the disk. This principle is applied in one type of speedometer.

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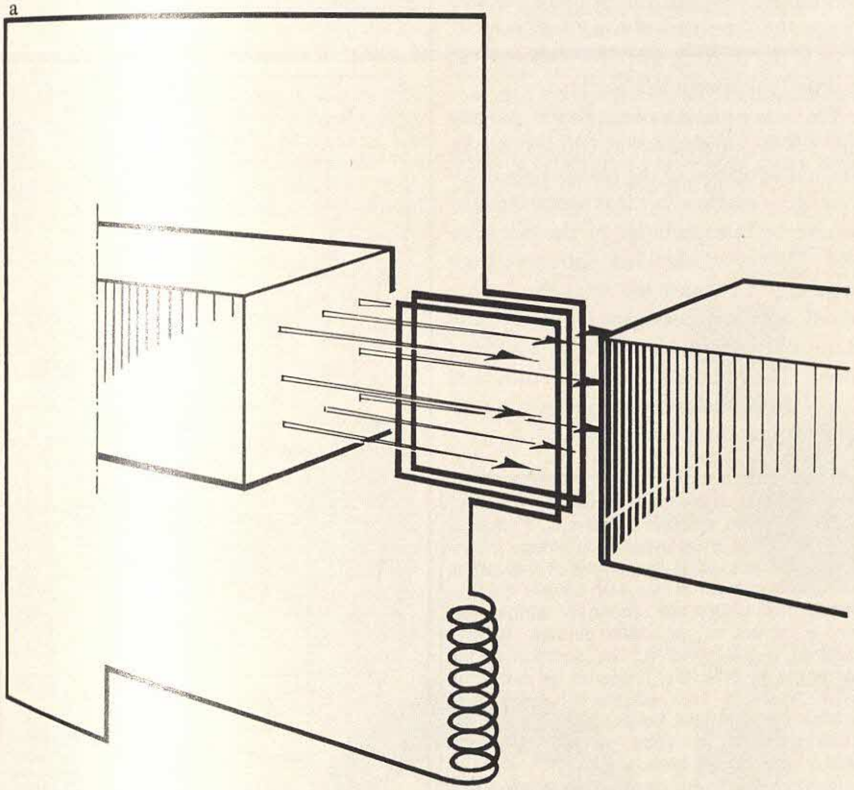

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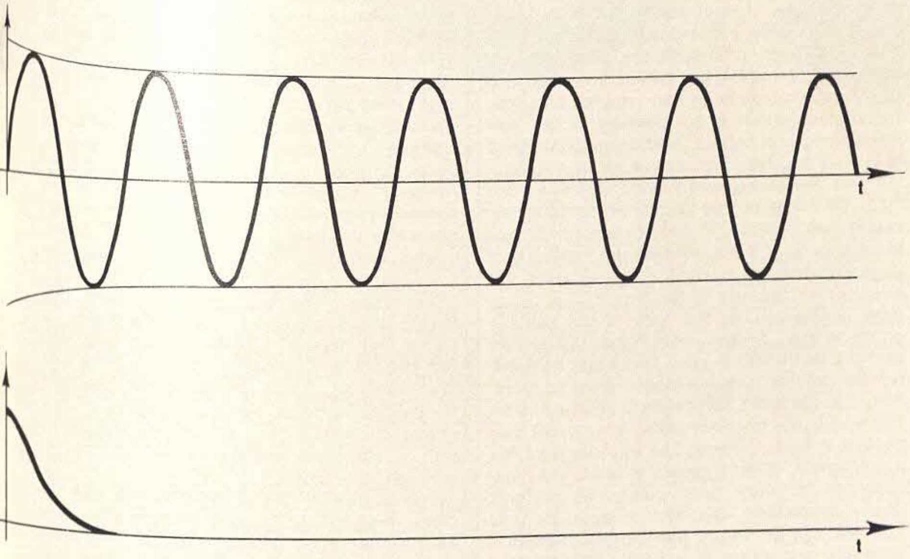

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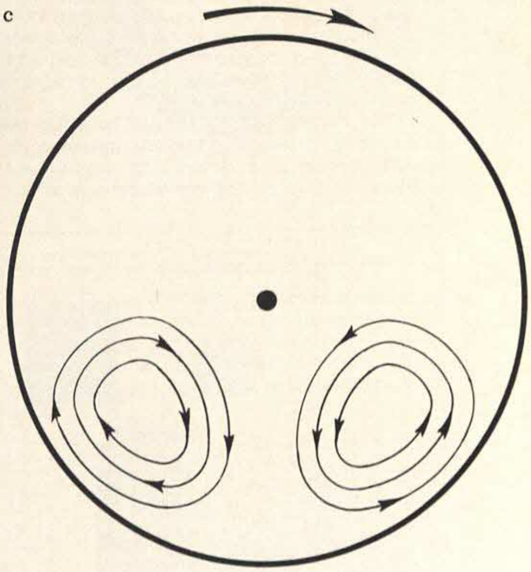

THE MAGNETIC PHENOMENA OF MATTER

diamagnetism, paramagnetism, and ferromagnetism

Experiments (either hypothetical or actual) with magnetic phenomena relating to induction vary considerably if the conditions are changed. Phenomena occurring with various types of conductors change if they occur in matter rather than empty space. For example, an electric current is induced in a coil of conducting material when the flux of the magnetic induction vector through the coil is made to vary, and the intensity of this current depends on the speed with which the flux varies within the coil. It will be shown here that the intensity of the induced current also depends on the medium in which the coil is immersed. Placing different substances between the turns of the coil varies the intensity of the phenomenon. This is the starting point for defining the magnetic properties of matter.

This examination of magnetic properties will be carried out at two levels: the first a description of the phenomena manifested by matter that is magnetized; the second an interpretation of the phenomena. However, detailed interpretations are difficult because the magnetic behavior of matter depends on its atomic and structural constitution and on temperatures. The theoretical interpretation of this class of phenomena requires a knowledge of quantum mechanics.

ROWLAND'S RING—One of the most fundamental items of equipment for studying magnetic phenomena in matter is Rowland's ring, invented by the American physicist H. A. Rowland. With its help, he was able to investigate many of the magnetic properties of matter. The ring consists of a toroidal winding of conducting material that can be connected to a generator of direct current. The ring shown here consists of many turns wound on a thin support that may be made, for example, from cardboard. Within this support is introduced the substance whose magnetic properties are to be examined. The dc generator is **P**, **I** is the switch, and **S** is the main, or induction, winding. A part of the main winding is covered by another winding, **S′**, which receives the voltage induced when the circuit of the principal solenoid is closed. The circuit of **S′** includes a ballistic galvanometer.

The toroidal winding chosen here has the advantage of ensuring that the magnetic circuit consists of a closed ring and will not, therefore, give rise to any dispersion of flux.

When switch **I** of the main winding **S** is closed, a current flows through the circuit. This current generates a magnetic field whose induction vector is parallel to the axis of the toroid. The establishment of this field causes a variation of flux within the secondary winding **S′**, and a current of very brief duration is thus induced in this winding. The duration of the current is so brief that it cannot be measured by an ammeter. This was the only instrument available at the time Rowland carried out his experiments, so he made use of a galvanometer of the ballistic type.

Galvanometers are said to be ballistic when they can be used for measuring a current that passes for an extremely brief period of time. The moving part of the galvanometer rotates through an angle that is proportional to the product of the current and the time it flows; that is, an angle proportional to the quantity of charge passing through the galvanometer. This type of instrument differs from conventional galvanometers in that conventional galvanometers measure the intensity of the current flowing in a conductor and are constructed in such a way that the oscillations of the moving part are of extremely short duration. The instrument thus comes quickly to rest in a new equilibrium position. In this position the torque in the wire (by means of which the moving part is suspended) is in equilibrium with the Lorentz forces because of the current that circulates in the coil. In the case of the ballistic galvanometer, on the other hand, the mobile part is constructed in such a way that its oscillations last for a much longer time; in practice, the maximum elongation is reached when the whole of the brief pulse of current has passed through the coil. The advantage of this arrangement is that it makes possible the measurement of very brief pulses of currents whose intensities vary with respect to time.

It will now be shown that currents flow in a Rowland ring when it is filled with different materials; also, a more modern system for measuring magnetic induction may be constructed.

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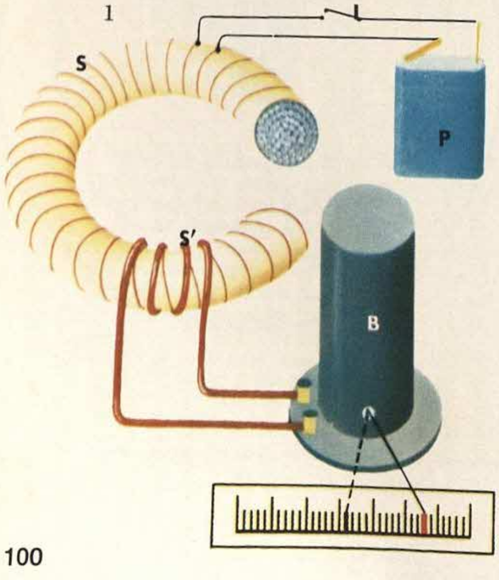

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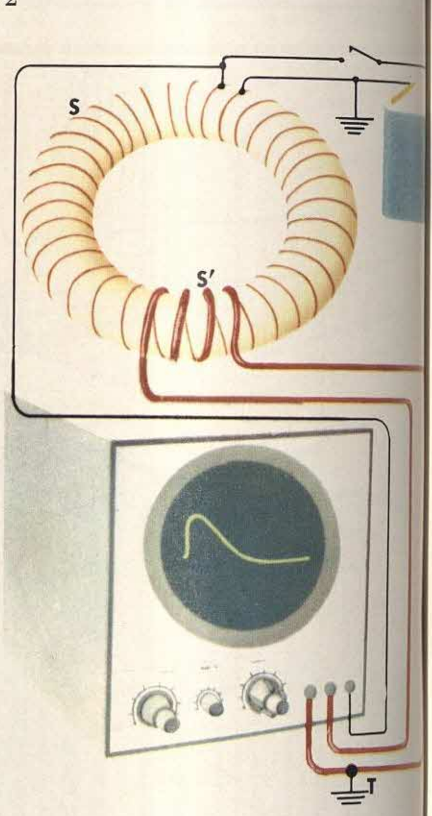


MEASUREMENT WITH THE OSCILLOSCOPE—When it was still necessary to use ballistic galvanometers, it was found that there were certain substances that, when inserted into a Rowland ring, did not permit an accurate measurement of the difference of effect with respect to empty space.

Today this difference is measured by a cathode ray oscilloscope. When the circuit supplying current to the primary winding **S** of Rowland's toroid is closed, the point **T** of the secondary circuit is grounded and then connected to the oscilloscope. The signal on the screen indicates the value of the voltage in the secondary circuit. The oscilloscope trace, rather than consisting of a horizontal line (which would correspond to a dc voltage), is a line that rises in proportion to the voltage that occurs in **S′**. This apparatus can be further improved. For example, the voltage sent to the oscilloscope can be amplified with a precision amplifier, or it can be compared with a standard voltage to see whether it exceeds it or not.

The switch in the primary circuit can be closed manually or by an automatic electronic arrangement. The switch is generally closed at periodic intervals in order to obtain a persistent trace on the oscilloscope. Today, the magnetic characteristics of materials are measured by apparatuses of this type.

3

THE PRINCIPAL TYPES OF BEHAVIOR—In this experiment, the most modern type of Rowland ring apparatus is assumed and will measure the magnetic properties of matter. The technique is as follows: the switch that supplies current to the winding **S** is closed, and a current thus flows in the secondary circuit **S′**. The product of the intensity of the current and the time of its duration, measured as the maximum height of the voltage produced in the secondary circuit, shows the intensity of the magnetic induction to which it has been subjected.

In Illustration 3a, the Rowland ring is in a vacuum or, what is practically the same thing, in air or some other gas at a pressure not greatly exceeding atmospheric pressure. The oscilloscope registers a characteristic trace.

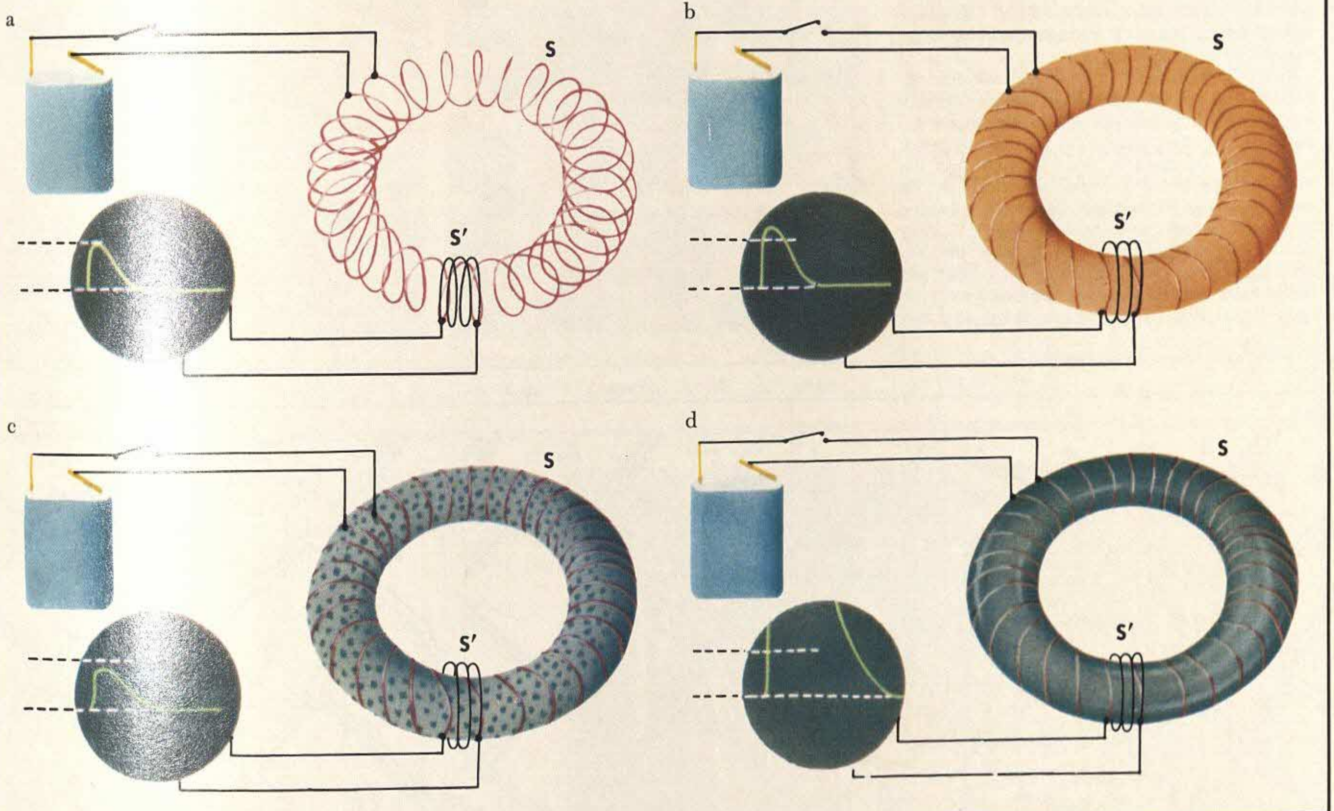
In Illustration 3b, a substance is introduced into the ring—an iron salt for example. The induction in the winding of the ring now becomes a little greater (the increase is of the order of a few parts per thousand). The substances that exhibit an increase of this order of magnitude are called paramagnetic. The salts of iron, cobalt, chromium, and manganese are all paramagnetic substances. The same applies to many oxides, the salts of the rare earths, and, among the gases, oxygen.

Illustration 3c shows that if a substance such as bismuth is introduced into the ring, the induction in the secondary circuit is slightly less than the one that would be obtained when the ring is immersed in empty space. A substance of this type is called diamagnetic. While a paramagnetic substance has a favorable effect on the establishment of the field, however slight this improvement may be, a diamagnetic substance exerts a small opposition. The noble gases are other examples of diamagnetic substances.

Illustration 3d shows that if the ring is wound on an iron core, an enormous increase in the value of the induction occurs. This increase may vary between one thousand and more than ten thousand times, and it depends on the type of material chosen and the iron content of the alloy employed. Substances of this type are called ferromagnetic.

Ferromagnetism is a property also displayed by many substances other than iron: nickel and cobalt, for example. The binary and ternary alloys of these metals, as well as the alloys with additions of other metals, are also ferromagnetic.

These are the three principal types of magnetic behavior displayed by matter.



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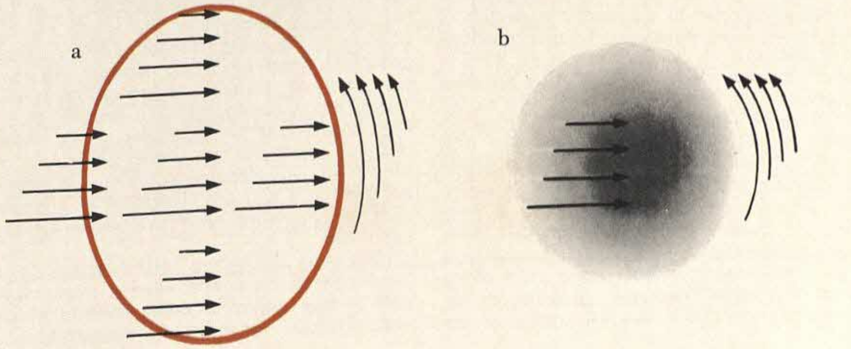
THE CAUSE OF DIAMAGNETISM—Among the three forms of magnetic behavior displayed by matter, the one most easily explained is diamagnetism. To this end an analogy is useful: assume a coil in which a current is flowing (Illustration 4a). A magnetic field whose initial value is zero is placed within the coil; the value then rises to a certain intensity. The horizontal arrows of increasing length in the illustration serve to represent the growing intensity of the magnetic field, while the curved arrows represent the growing intensity of the induced current that circulates in the coil and reduces the intensity of the inducing field. This phenomenon occurs both when the charges subject to the action of the magnetic field are moving in a conductor and when they are free in space. Charges of the latter type may be represented, for example, by the ions of a rarefied gas or by the electrons of an atom. Illustration 4b shows the charge that is distributed within an atom; the charge is not stationary, even though it may be difficult to define the exact trajectory along which it moves. However, it moves, and its motion is such that its speed of rotation diminishes when a magnetic field is induced around the atom. The charge will thus tend to diminish the magnetic field that surrounds the atom. The phenomenon of diamagnetism, therefore, possesses two very important characteristics: it is present in all atoms because all the atoms in the periodic system have the characteristic of having an electric charge in motion; and it acts in a sense that opposes the inductive field.



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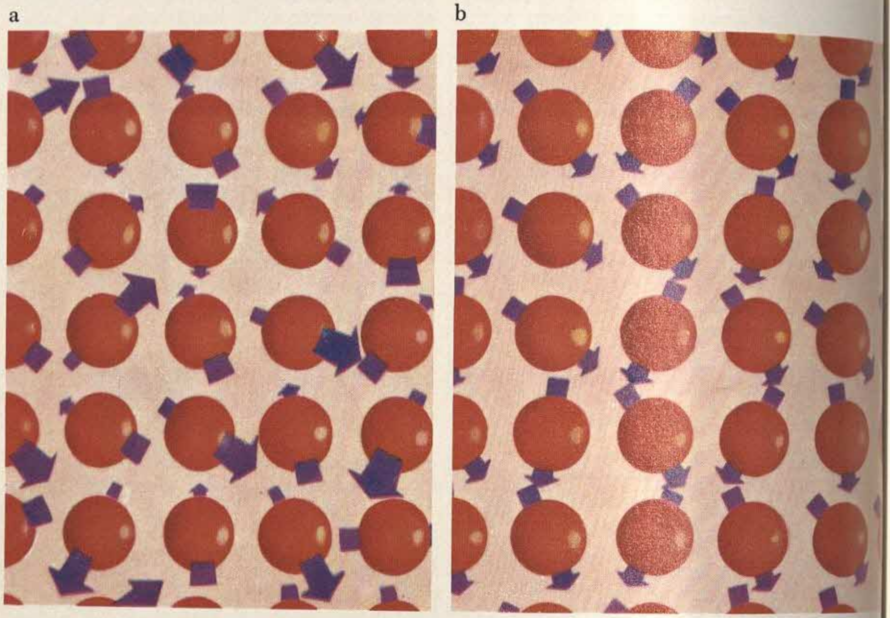
PARAMAGNETISM—The fact that atoms possess magnetic currents enables each atom to be thought of as a small magnet made up of a microscopic mesh of current. For the moment, the interest is in the phenomenological aspect of the problem, and it is, therefore, sufficient to consider the atoms of a block of matter as so many tiny magnets. These tiny magnets, when far away from a magnetic field, are all oriented at random. A magnetic field, on the other hand, orients them all in the same direction. When they are oriented in this manner they strengthen the magnetic field that generated them. However, there is no substance in which this straightening of the axes of the elementary magnets occurs in a perfect manner, and in the greater part of the substances it is achieved only partially. Moreover, not all atoms produce a magnetic field of the same intensity.

It has already been shown that the diamagnetic effect is present in all atoms. A substance only displays paramagnetic behavior if the magnetic field produced by the alignment of the tiny magnets is more intense than the field produced by the diamagnetism of the substance itself. When the substance is heated to a high temperature, the thermal oscillations of the atoms again introduce disorder into the arrangement of the magnetic axes, and this leads to a reduction of the paramagnetic effect. Illustration 5a shows paramagnetic material consisting of a network of tiny magnets whose axes are arranged in a disorderly manner in the absence of a magnetic field. Illustration 5b shows the same material with the axes arranged in a more orderly (but still imperfect) manner when such a field is acting on it.



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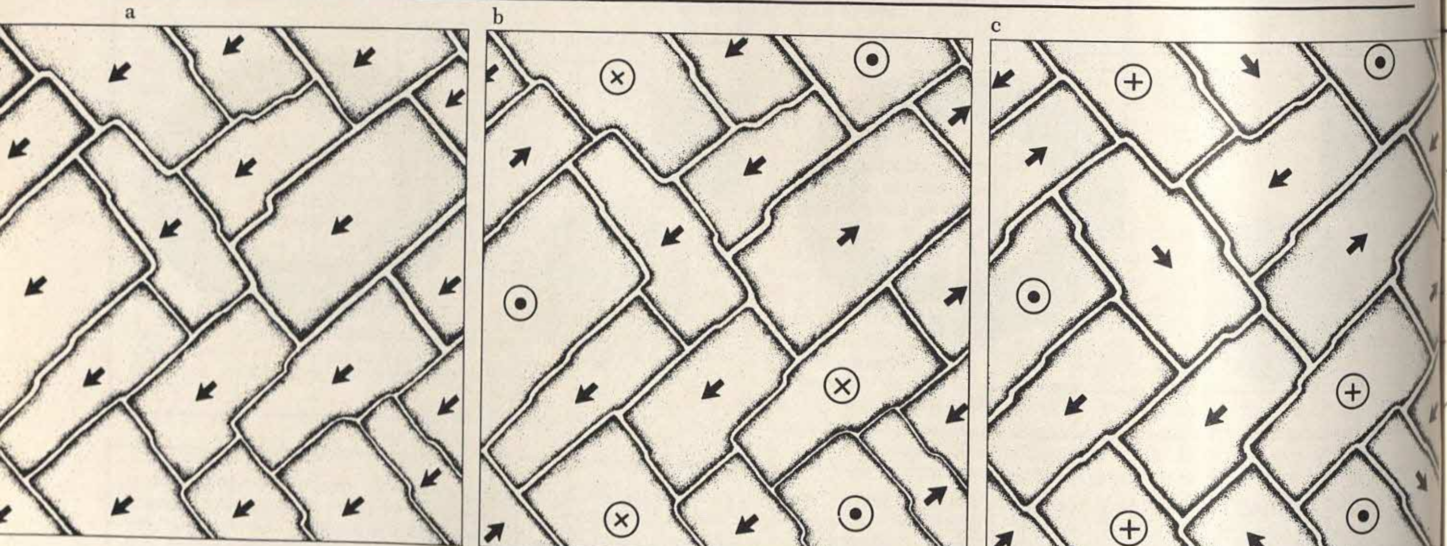

FERROMAGNETISM—The cause of ferromagnetism is completely different from that of either diamagnetism or paramagnetism. In fact, whereas the phenomenon in the first two cases is exclusively due to the atomic properties of matter, ferromagnetism also involves phenomena that concern the structure of the solid in which the atoms are organized. It is not even necessary to destroy completely this atomic organization of the solid in order to cause the ferromagnetic phenomena to disappear; it is quite sufficient to heat the solid beyond the Curie point, that is, to the temperature at which the thermal oscillation of the atoms is sufficient to destroy the organization that gives rise to ferromagnetism. The Curie temperature is always lower than the melting point of the solid and varies from one substance to another. A rather summary illustration of the phenomenon of ferromagnetism can be given:

Illustration 6a shows that in a ferromagnetic substance there exist groupings of atoms that can be compared to microcrystals, in which the magnetic moments of the atoms are all oriented in the same direction. Each of these groupings, which are called domains and contain from one thousand to one million billion atoms, has a strong magnetic moment of its own. However, as this illustration shows, under ordinary conditions the magnetic moments of the various domains are all oriented in different directions and the substance as a whole does not, therefore, seem to possess a magnetic field.

Illustration 6b shows what happens to a ferromagnetic substance when a weak magnetic field is applied to it. The domains, which were previously oriented in a completely random manner, now begin to orient themselves in the direction that might be called the direction of the inducing magnetic field. The orientation of these magnetic fields causes an increase in the intensity of the magnetic field that can be observed from outside.

If the intensity of the inducing magnetic field is increased still further, an almost completely uniform orientation of the domains is observed, and this brings about the enormous increase in the intensity of the induced magnetic field (Illustration 6c). Despite the comparison of domains to something like microcrystals, this comparison is valid only as regards the dimensions of the domains, which, notwithstanding the large number of atoms they contain, have maximum transverse dimensions of the order of 30 to 300 μm (microns).

INDUCTANCE | an important parameter of electric circuits

Inductance is an important characteristic of electric circuits. When a current passes through a conductor, energy is expended to maintain the current against the resistance of the conductor. Energy is also expended to create the magnetic field that surrounds the conductor with its lines of force. This subtraction of energy results in an attenuated current as soon as a connection is made; the opposite effect is observed when the current is interrupted. The magnetic field, in which energy has been stored, decays; this induces a current which diminishes gradually, flowing through the conductor and compensating exactly for the extra current received when the circuit was opened. When direct current is used, inductance occurs only in the instants when the electron flow begins and when it ceases. When alternating current is used, the phenomenon occurs continually, at each cycle.

The phenomenon of inductance occurs in every circuit, but it can be increased by the structure of the circuit. If the circuit is in the form of a solenoid, or if it contains a ferromagnetic substance, then the energy stored in the magnetic field associated with the current is very large. In such a case, the inductance of the circuit has quite different characteristics under alternating current than it has under direct current. Inductance is an important consideration in power circuits. It is also important in electronic circuits, even though very little power is used.

In electric power circuits, the energy is transmitted by means of alternating currents because they are readily transformed from low to high voltages, and vice versa. The insertion of machines with certain inductance characteristics into a network can cause the voltages to become out of phase with the currents from the generator, preventing power from being drawn from the circuit. If this happens, the network must be rephased with special equipment. The study of inductance characteristics is, therefore, very important in electrical engineering.

In oscillating electronic circuits, the inductance (together with the capacitance) determines the value of the oscillation frequency. Even the wires connecting various parts of a circuit (such as transistors, capacitors, and resistances) have inductances of their own, which affect the inductances introduced into the circuit by the several components. For this reason the design of a circuit must consider the inductances of all components and the wires connecting them.

Inductance effects must be considered in pulse circuits also. In the circuit for counting the pulses of a gamma radiation counter, for example, it is important that the pulses have a rectangular form. (The rectangular form of a pulse is mathematically described by breaking it down by means of a Fourier series—developed by the French mathematician Jean Fourier—in which the high frequencies are those that give the perfect rectangular form.) However, these are the same frequencies that are most affected by the inductance of the circuit, and it is necessary that the circuit be designed to minimize induction problems.

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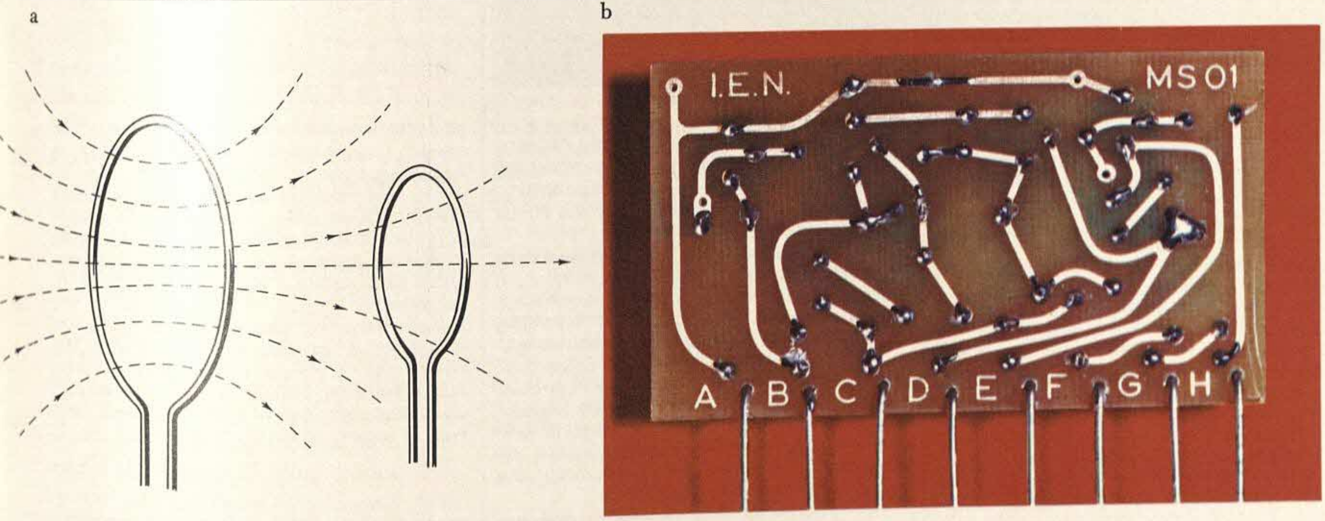

THE MUTUAL INDUCTANCE OF TWO CIRCUITS—Two loops are brought sufficiently close together to ensure that the magnetic field associated with current in the first conductor affects the second conductor (Illustration 1a). If a time-varying current passes through the first conductor, the magnetic field surrounding the loop will also vary with time. A magnetic field is induced through the second coil that also varies with time, and this induces a current in the second coil. The intensity of the magnetic flux associated with the second loop depends on the rate of variation of the current in the first circuit (so called even though it consists of only a single coil) and on the geometrical arrangement of the two coils. The proportionality factor relating the intensity of the current in the primary circuit to the intensity of the current induced in the secondary circuit is called the mutual inductance of the two circuits.

The mutual inductance of two circuits is measured in a unit called a henry (named for the American physicist Joseph Henry). Two circuits have a mutual inductance of one henry when a voltage of one volt is induced in one of the circuits by a current in the other circuit that varies at the rate of one ampere/sec.

Illustration 1b shows the back of a printed circuit—the side on which the connections are printed. This must be a low-frequency circuit because many wires run almost parallel for fairly long distances. In a high-frequency circuit, the mutual inductance between two wires close to each other leads to a considerable transfer of energy from one wire to the other, thereby impairing the functioning of the circuit. In high-frequency circuits, the conductors are either screened with a metallic sleeve connected to the ground or they are arranged so that they run in an oblique direction to one another.

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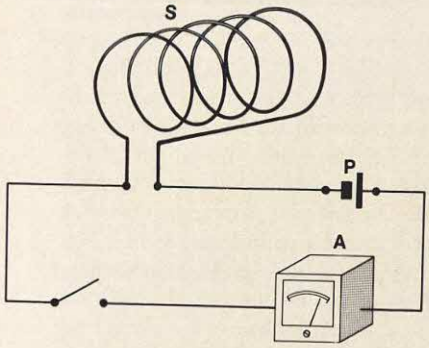

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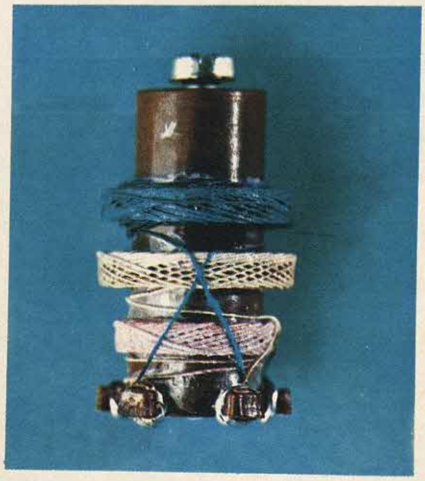

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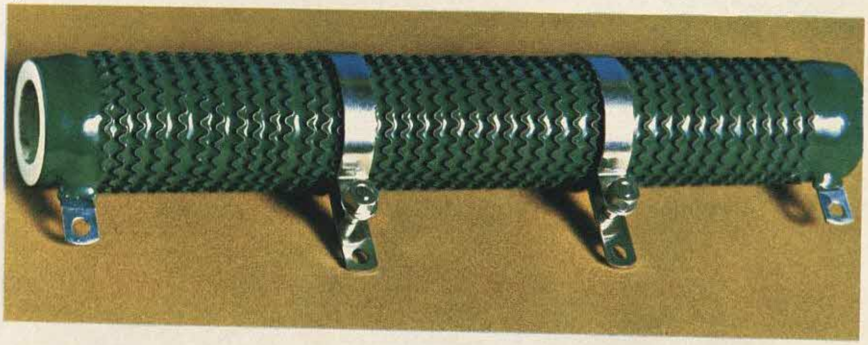

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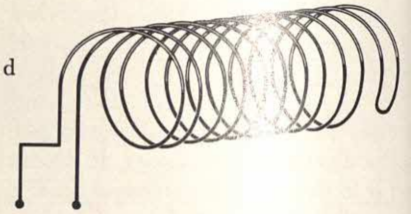

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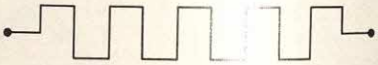


SELF-INDUCTION— Induction also occurs when electrons begin to flow in a circuit.

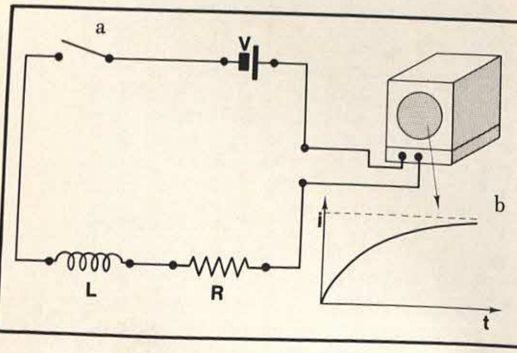
The first diagram (Illustration 2a) shows a large number of coils arranged in parallel to form a solenoid **S** and connected to a battery **P.** When the circuit is closed, the pointer of the ammeter **A** should be instantaneously deflected, indicating the presence of a current in the circuit; in actual practice, the pointer rises very slowly and reaches this maximum value only after a certain time. When the current first enters the solenoid, it generates a magnetic field that opposes the current. Once the current has been established, the magnetic field no longer impedes the current, because it is generated only by a current whose intensity is changing. The current then must overcome only the resistance of the coil. The electromotive force that initially opposes the passage of the current is called the self-induced electromotive force—that is, the electromotive force induced by the circuit itself.

The coil shown in Illustration 2b serves as an inductance in a high-frequency circuit. It consists of several layers of conductor windings that are glued together by insulating paint. Illustration 2b′ shows an inductance system for low-frequency circuits. It consists of a solenoid wound on an iron core, which increases the value of the inductance because it prevents the dispersion of the magnetic flux.

If a circuit is to function as desired, resistances, inductances, and capacitances—the so-called concentrated constants—must be known. However, a resistor can also have a capacitance and an inductance, just as an inductor can have an ohmic resistance. These effects must be taken into account. Illustration 2c shows a resistor that is a wire wound on a ceramic cylinder. The winding is in the shape of a solenoid, and it has a certain inductance.

If the frequency used is low, no problem is presented. If the frequency is high, on the other hand, a noninductive resistor is used. Illustration 2d is a diagram of such a resistor: a double solenoid. In circuit diagram, this type of resistor is shown in Illustration 2e.

3



A CIRCUIT WITH INDUCTANCE AND RESISTANCE—When the circuit diagramed in Illustration 3a is closed, the current does not instantaneously reach its maximum value as given by Ohm's law. The differential equation that describes this circuit can be derived and solved to give the value of the current at any time. Let **i** denote the value of the current at any instant, **L** the value of the inductance, **R** the value of the resistance, **t** the time, and **V** the voltage of the generator: the current increases according to the law

$$i = (1 - e^{-Rt/L})V/R.$$

Illustration 3b plots current strength as a function of time. The opposing current caused by the inductance decays exponentially. The time in which the self-induced current falls to 1/**e** of its initial value is called the time constant of the circuit. This constant is given by **t = L/R.** When **L** = 1 henry and **R** = 1 ohm, the time constant is 1 sec.

Inductances are used in circuits with tubes and transistors, but they are usually avoided in microcircuits because of the difficulty of making them sufficiently small.

THE PHENOMENON OF FERROMAGNETISM

interpretation at the microscopic level

The properties of matter are frequently exploited in technology. Practical applications are derived from the theoretical knowledge of the phenomena governing matter, as in the construction of diodes and transistors from the knowledge of the phenomena of semiconductors.

On the other hand, some applications have preceded the knowledge of phenomena, the theory following the employment of unexplained properties of matter, sometimes with great difficulty. Such is the case of ferromagnetism, where the applications of empirical knowledge have suggested a considerable number of experiments through which theoreticians have sought a microscopic explanation of the phenomenon already in use.

Ferromagnetic substances are those displaying a strong residual magnetization, even when they are subjected to the action of an external magnetic field that is subsequently annulled.

Magnetism and the behavior of ferromagnetic substances have been known with some accuracy for two centuries, but the principal applications were achieved after electric energy came out of the physics laboratories and became a means of transporting mechanical energy from its place of production to separate places of utilization.

The study of ferromagnetic phenomena was initially limited to the study of alloys most suitable to the construction of very soft magnetic laminates for transformers and generators. Such studies were subsequently extended to the preparation of materials for permanent magnets, magnetostrictive materials, and ferrites. The greater part of these applications were made by experimenting with a limited knowledge of the microscopic aspects of the phenomenon, providing an unsure guide to the properties of the matter involved. Permanent magnets, as well as electromagnets, are used to produce fields of considerable strength and constancy. A host of devices depend on them for operation. The best materials for this use are precipitation-hardened alloys with no essential carbon. Permanent magnets are used in loudspeakers, magnetos, many kinds of meters, and various telephone receivers.

The accompanying illustrations present and explain some of the aspects of current ferromagnetic theory.

THE CURIE TEMPERATURE—Ferromagnetic substances are those displaying a strong residual magnetization, even when they are subjected to the action of an external magnetic field that is subsequently annulled.

A characteristic common to all ferromagnetic substances is that they completely lose the residual field when they are heated above a certain temperature known as the Curie temperature. This temperature, which depends on the substance, represents a limit above which the ferromagnetism disappears completely and the substance becomes paramagnetic. Above the Curie point, the molecular forces responsible for ferromagnetism cease to exist.

The existence of the Curie temperature neatly separates the domain of ferromagnetism from that of paramagnetism, suggesting some very important hypotheses for the theory of ferromagnetism. One of these hypotheses is that ferromagnetism is attributable to the presence of atoms within matter—atoms that are associated with elementary magnetic dipoles. These magnetic dipoles become oriented under external action such as a magnetic field. A certain amount of energy has to be expended to produce this orientation and the system of oriented magnetic elements becomes stable. This stability is produced by the presence of bonds that can be destroyed by a sufficiently energetic action, such as thermal action. Heat produces a vibration of the atoms within the substance. Once the vibrational energy associated with the heat content of the system exceeds a certain value, it is sufficient to break the bonds that held the atoms (or microscopic magnetic systems) in alignment.

This illustration shows the significance of the Curie temperature $\mathbf{T_c}$. $\mathbf{E_0}$ is the bond energy between the oriented magnetic systems. As a first approximation, this may be regarded as being constant at the various temperatures. The red curve represents the increase of vibration energy of the atoms of the substance. When this vibration energy is more or less equal to the bond energy, it is possible for the bonds to break and the ferromagnetic behavior of the substance to disappear. This hypothesis has been verified.

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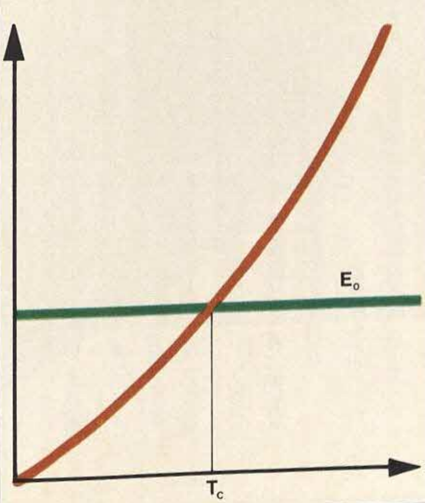

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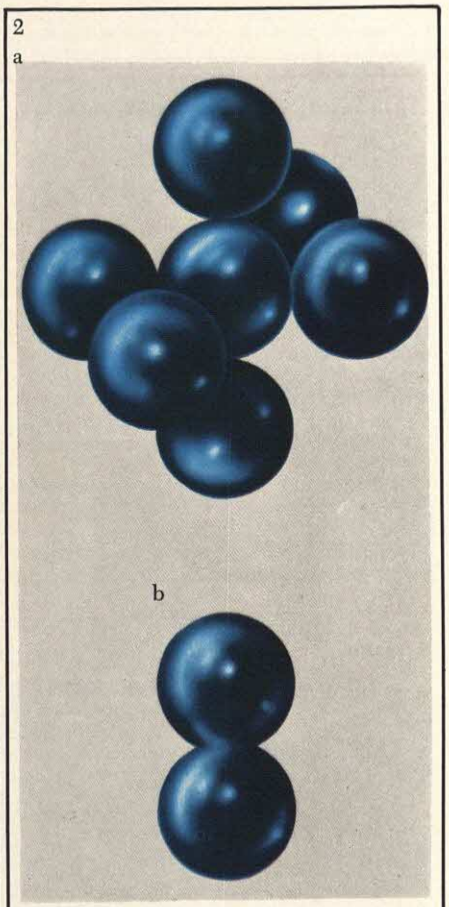
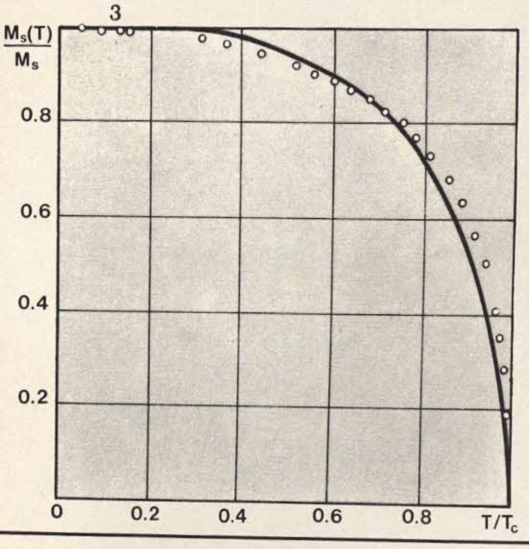


THE WEISS FIELD—The bonds mentioned in the previous section arise from a quantum mechanical phenomenon known as exchange forces. The effect of these exchange forces is to cause a communication between the elementary magnetic dipoles such that they all tend to line up in the same direction. The total effect on one particular dipole due to all the others is known as the Weiss field. For this particular dipole to move out of the common direction of alignment it has to overcome this Weiss field. The Curie temperature then is that temperature at which the vibrational energy becomes greater than the stabilizing energy of the Weiss field.

The observation of atoms arranged close to each other in a crystalline structure and, therefore, linked to each other (Illustration 2a) reveals that they can possess electrons in common, and that in most cases these shared electrons are found in external orbits (Illustration 2b). Although these external electrons actually belong to two different atoms, they are bound to the same system; according to the state of the atom, the spins of these electrons may be forced to change direction. For example, instead of being parallel, the electrons may arrange themselves in an antiparallel manner. Such a change in orientation implies a change of energy. It is these electrons in external orbits that give rise to the elementary magnetic dipoles, and their relative orientation determines the energy of the system.

3



SPONTANEOUS MAGNETIZATION — If the Weiss hypothesis is true, the Weiss field must produce a magnetization, even in the absence of an inducing magnetic field. Magnetization produced in this manner is called spontaneous magnetization. The intensity of this magnetization depends on the temperature and can be verified experimentally.

This illustration shows the ratio between spontaneous magnetization observed at various temperatures and the maximum value of this magnetization. The substance represented is nickel. The temperature varies from absolute zero to the Curie temperature, where magnetization disappears completely. Plotted points represent values determined by experiment; the continuous line is the theoretical curve, calculated on the basis of the Weiss hypothesis. The abscissa shows the ratio between the experimental temperature and the Curie temperature. Comparison of the line with the plotted points shows the close agreement between theory and observation.

THE DE HAAS-VAN ALPHEN EXPERIMENT— The Weiss field is not the only factor contributing to residual magnetization in ferromagnetic phenomena. A conspicuous effect may also be attributed to oriented spins of the atomic electrons. This can be deduced from a simple consideration:

The electrons revolve around the atomic nuclei and have both a spin angular momentum (momentum resulting from rotation about their own axis) and an orbital angular momentum (momentum resulting from their revolution at a certain speed in closed orbit). The orientation of both these magnitudes can make a contribution to the spontaneous magnetic field. Which of the two is more important can be determined by microscopic experiments. The graph illustrates such an experiment.

In the de Haas-van Alphen experiment, a rod of ferromagnetic material is suspended inside a solenoid by means of a thin wire. A very intense current can be passed through the solenoid in either direction. Even the slightest action (which has the effect of rotating the rod) does not meet any significant resistance, since the opposition of the thin wire to this

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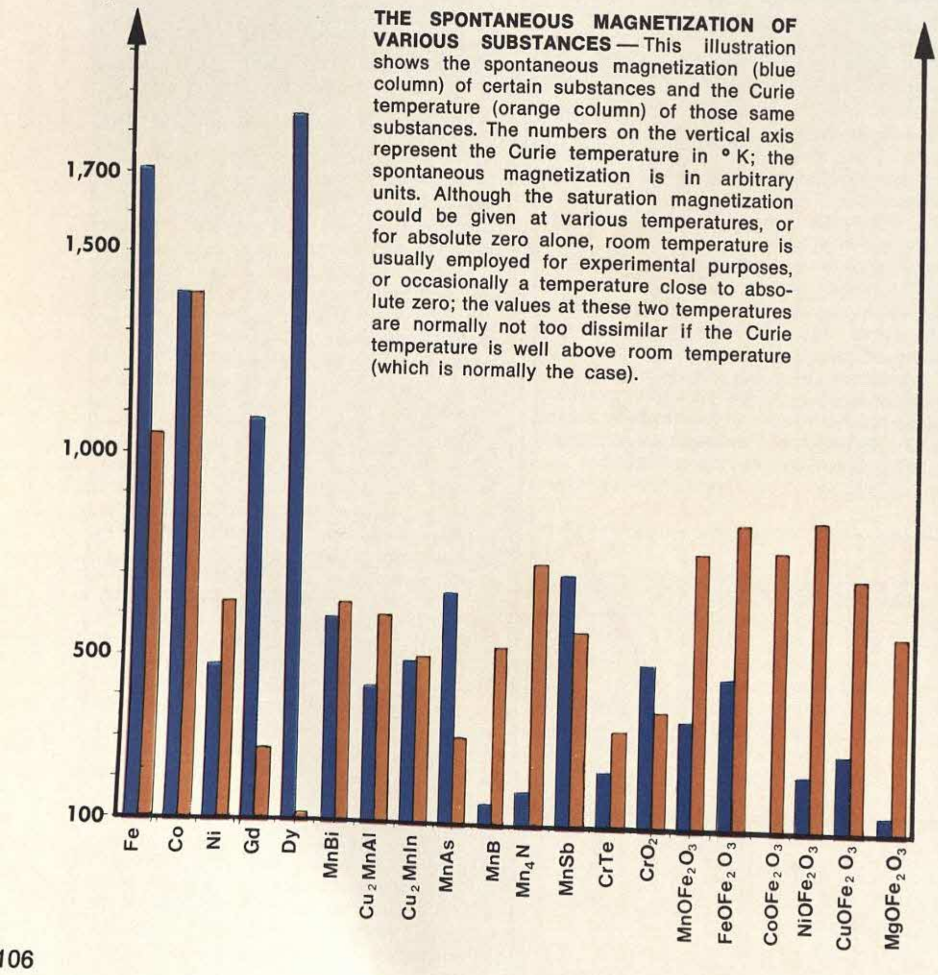

THE SPONTANEOUS MAGNETIZATION OF VARIOUS SUBSTANCES — This illustration shows the spontaneous magnetization (blue column) of certain substances and the Curie temperature (orange column) of those same substances. The numbers on the vertical axis represent the Curie temperature in °K; the spontaneous magnetization is in arbitrary units. Although the saturation magnetization could be given at various temperatures, or for absolute zero alone, room temperature is usually employed for experimental purposes, or occasionally a temperature close to absolute zero; the values at these two temperatures are normally not too dissimilar if the Curie temperature is well above room temperature (which is normally the case).

FERROMAGNETIC RESONANCE — Nuclear magnetic resonance and electronic spin resonance are modern methods for study of the structure of matter and for certain types of analysis. Experiments similar to these techniques may be carried out to shed light on ferromagnetic phenomena.

A rotating magnetic field produced in a solenoid by an alternating voltage of very high frequency—or by means of microwaves—can cause the residual magnetic field of a piece of ferromagnetic substance to precess about the direction of a static field. If the frequency is varied, it can be observed that energy is taken from the field when the precession of the magnetic vector of the test piece undergoes a transition between two energy levels.

The magnetic field vector of the ferromagnetic substance, under such conditions, behaves similarly to a quantity whose magnitude can assume only specific energy levels. If the vector is excited to rotation by oscillation of the external field at radio frequency, it will vary its own energy only when it has reached a threshold governed by the intensity of the magnetic field in which it is immersed and by the variations of that field.

Such an experiment, first carried out in 1946, also highlights the importance of electronic spin in ferromagnetism.

The illustration shows a test piece (in the form of a thin lamina) within a variable field magnet, brought to the extremity of a wave guide for microwaves. Measurements made with this apparatus show (with some variation in values) the importance of electron spin in the formation of residual fields in ferromagnetic substances.

The table accompanying the illustration shows the ratio between the magnetic orbital moment and the spin moment for certain substances. This ratio (represented by ϵ) was found by means of the method described above.

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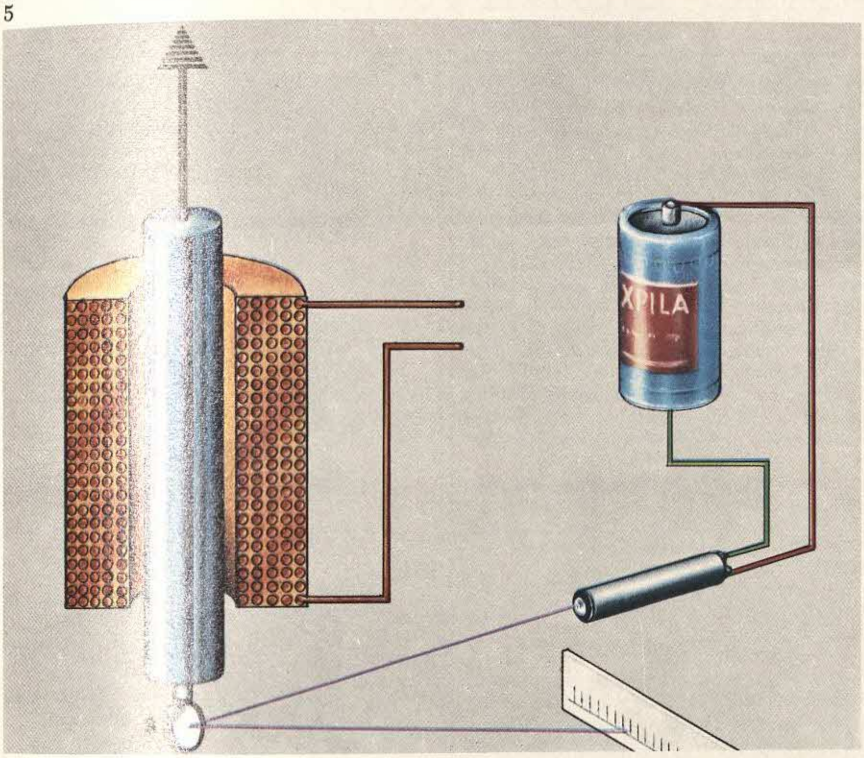


movement is very small. The slight resistance to rotation is similar to that met in the suspension of a galvanometer.

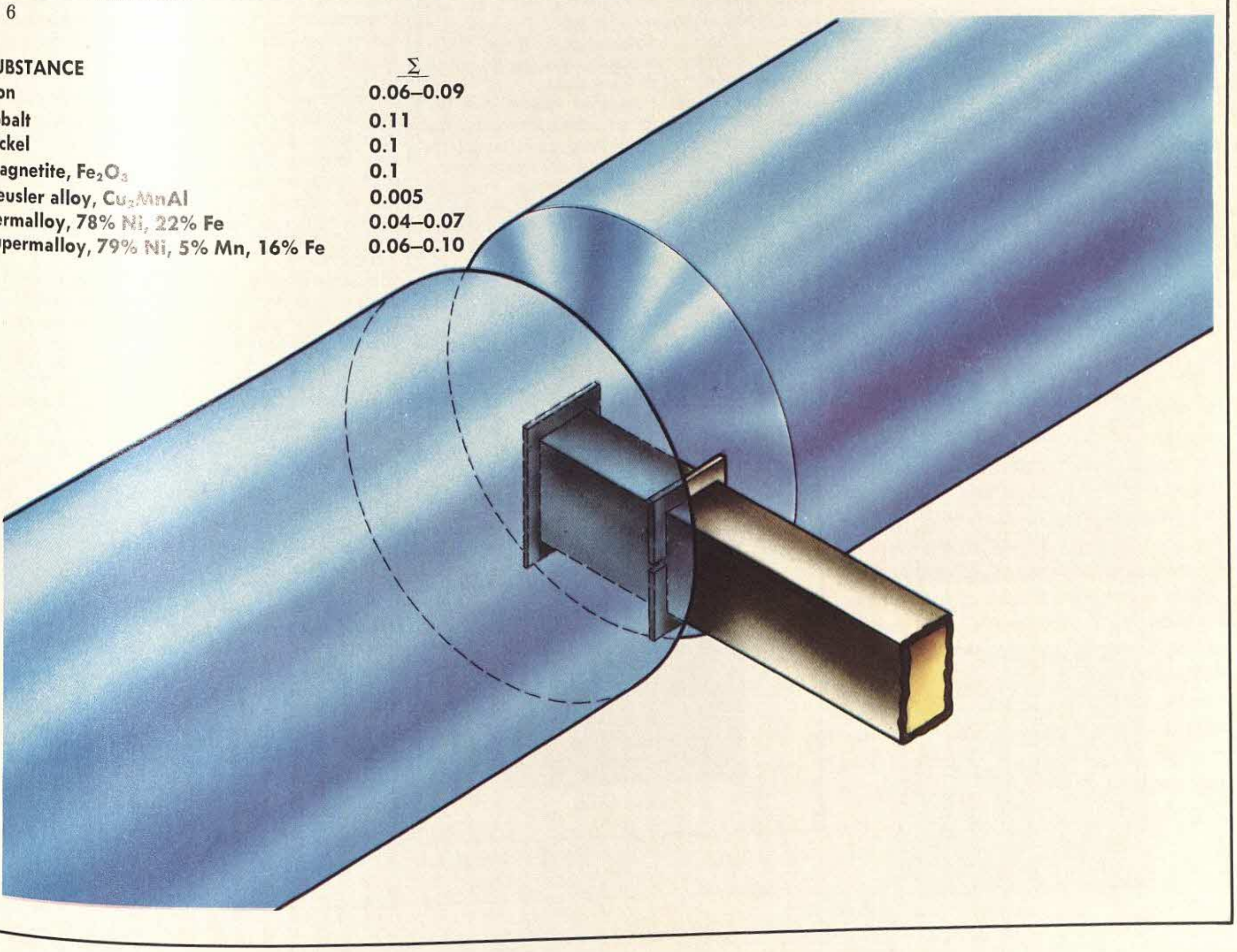
A strong current is passed through the solenoid; its direction of flow is then inverted, resulting in a rotation of the rod.

A variant of this experiment is to suspend the rod by a means more resistant to rotation, in order to impart an angular acceleration to the bar's rotation about its vertical axis. Such a configuration would permit observation of the current induced in the solenoid.

The theory relating to the de Haas-van Alphen arrangement is complex. It is sufficient to note that by means of the deflection of the light beam reflected by the mirror **S** attached to the rod, the amount of contribution to ferromagnetism obtained from the electrons revolving in their orbits (rather than from their spin) may be deduced. The predominant contribution is that due to the spin of the electrons; that due to their movement in orbit is almost zero and amounts to no more than about 5 percent of the ferromagnetism resulting from their spin. This value is even less in alloys with pronounced ferromagnetic properties.

6

SUBSTANCE	Σ
iron	0.06–0.09
cobalt	0.11
nickel	0.1
magnetite, Fe_2O_3	0.1
Heusler alloy, Cu_2MnAl	0.005
Permalloy, 78% Ni, 22% Fe	0.04–0.07
Supermalloy, 79% Ni, 5% Mn, 16% Fe	0.06–0.10



FERROMAGNETIC DOMAINS

theory and verification

The theories of ferromagnetic phenomena that occur at the microscopic level have reached a high degree of perfection and are now being used to prepare substances with particular properties for practical applications.

Both theory and experiment have identified materials with varying degrees of permeability or coercive force, a product of physics research in the field of the solid state applied to the interpretation of ferromagnetic phenomena.

A typical example of this research and application is alnico V, a material used for permanent magnets that allows them to lift several hundred times their own weight of iron. Alnico V was developed only after a precise interpretive theory of ferromagnetism was formulated, and after techniques for the preparation of certain materials and alloys were perfected. Similar efforts preceded the development of magnetic materials of very high permeability, such as Permalloy. These ferromagnetic materials are essential parts of the machines of modern civilization; for example, electric motors and generators, transformers, telephones, loudspeakers, and ultrasonic transducers. In addition, ferromagnetic materials are used in geophysical prospecting; the method measures the magnetic effects produced by varying concentrations of ferromagnetic materials.

The accompanying illustrations present what has been termed the theory of ferromagnetic domains without attempting to explain the characteristics of these domains, their dynamics under magnetization, or their dynamics in the absence of an external field.

In studying the illustrations, it should be understood that there are microscopic phenomena by which a substance can become ferromagnetic and exhibit a permanent field; and that it is possible for this to occur when the electronic spins of the atoms become oriented. Such an understanding, however, does not entirely satisfy a complete theory of ferromagnetism. Such a theory must also be capable of explaining the existence of high permeability—or of a high coercive field—in certain substances. Explanation of these characteristics may be found at an intermediate level, between the atomic level and crystallographic level, as shown in the illustrations.

THE FERROMAGNETIC DOMAINS—If a body of ferromagnetic material having a residual field is examined, it can be observed that the value of the intensity of this field is much less than that that could be obtained by subjecting the same body of material to the action of an external field. This means that the elementary fields originating from such processes as the orientation of the electron spins (under Pauli's principle) will not have the same intensity under ordinary conditions as they would have within the influence of an external field. The problem of explaining this difference in intensity is complicated by a law under which the internal field augments as the intensity of the external field increases.

Explanation of these phenomena can begin with the following hypotheses:

Below the Curie temperature, a ferromagnetic substance can be considered as being formed of small portions, called domains. These are spontaneously magnetized and, therefore, have a magnetic moment.

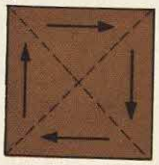
The total magnetic moment of the substance is equal to the vector sum of all the individual magnetic moments.

An example of the foregoing is provided in Illustration 1a, which shows four such domains within a crystal. These domains are oriented in opposed pairs in such a way as to annul the overall field. At a distance, this crystal does not seem to possess a permanent field.

In Illustration 1b a polycrystal is represented. Its domains are not bounded by the same limits as its component crystals, but are practically independent of them. The magnetization within each domain has a random orientation. The total residual magnetization, taken over the polycrystal as a whole, is nil, or of very small value. If, however, the domains become oriented in a particular direction, the same polycrystal would have a permanent residual field. It follows that an interpretation of this phenomenon of orientation must include an explanation of the particular force revealed by the plotting of a magnetization curve such as that shown in Illustration 3.

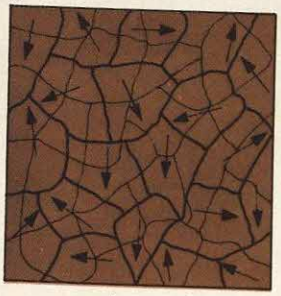
1

a



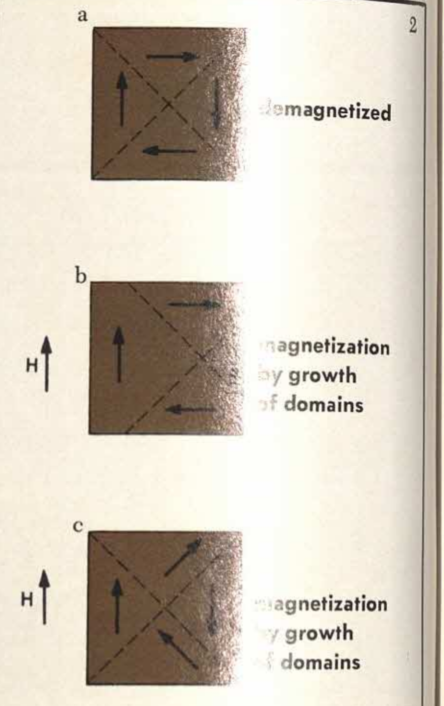
single crystal

b



polycrystal

2



THE PROCESSES OF MAGNETIZATION—These figures show how the phenomena of magnetization within a monocrystal can be interpreted. The hypotheses on which they are based have been verified by experiment, although the experimental justifications are too detailed to be provided.

Illustration 2a shows a monocrystal before it is subjected to the action of an external magnetic field. It appears to be divided into four domains, each of which is oriented in such a way as to cancel the field of the opposite domain. It is significant that the boundaries of these domains are independent of the crystallographic boundaries of the substance itself.

In Illustration 2b the monocrystal has been subjected to the action of an external field **H**, with a consequent alteration of its microscopic magnetic state. The domain on the left has extended its boundaries toward the right and expanded at the expense of the other three domains. The domains on the top and bottom have decreased in size, but to the same extent, since they have remained oriented in parallel and opposite directions; their combined field is still zero. The domain on the right has also become smaller and its action has become negligible in comparison with the domain on the left. These new boundaries will remain after the inducing field is removed and the specimen will remain magnetized.

In Illustration 2c a permanent magnetization has been created without movement of the domain boundaries. The presence of the inducing field **H** has not influenced the directions of the two domains oriented parallel to it; however, the other two domains have been partially oriented by that field. The superposition of the two top and bottom magnetizations thus gives a residual field that is different from zero. This phenomenon is called magnetization by rotation of the domains.

3

THE INTERPRETATION OF THE MAGNETIZATION CURVE—An understanding of the ferromagnetic domains and the processes of magnetization leads to the interpretation of the magnetization curve shown in this illustration. As in the preceding illustration, the results of experiments are presented without attempting to offer their experimental justification.

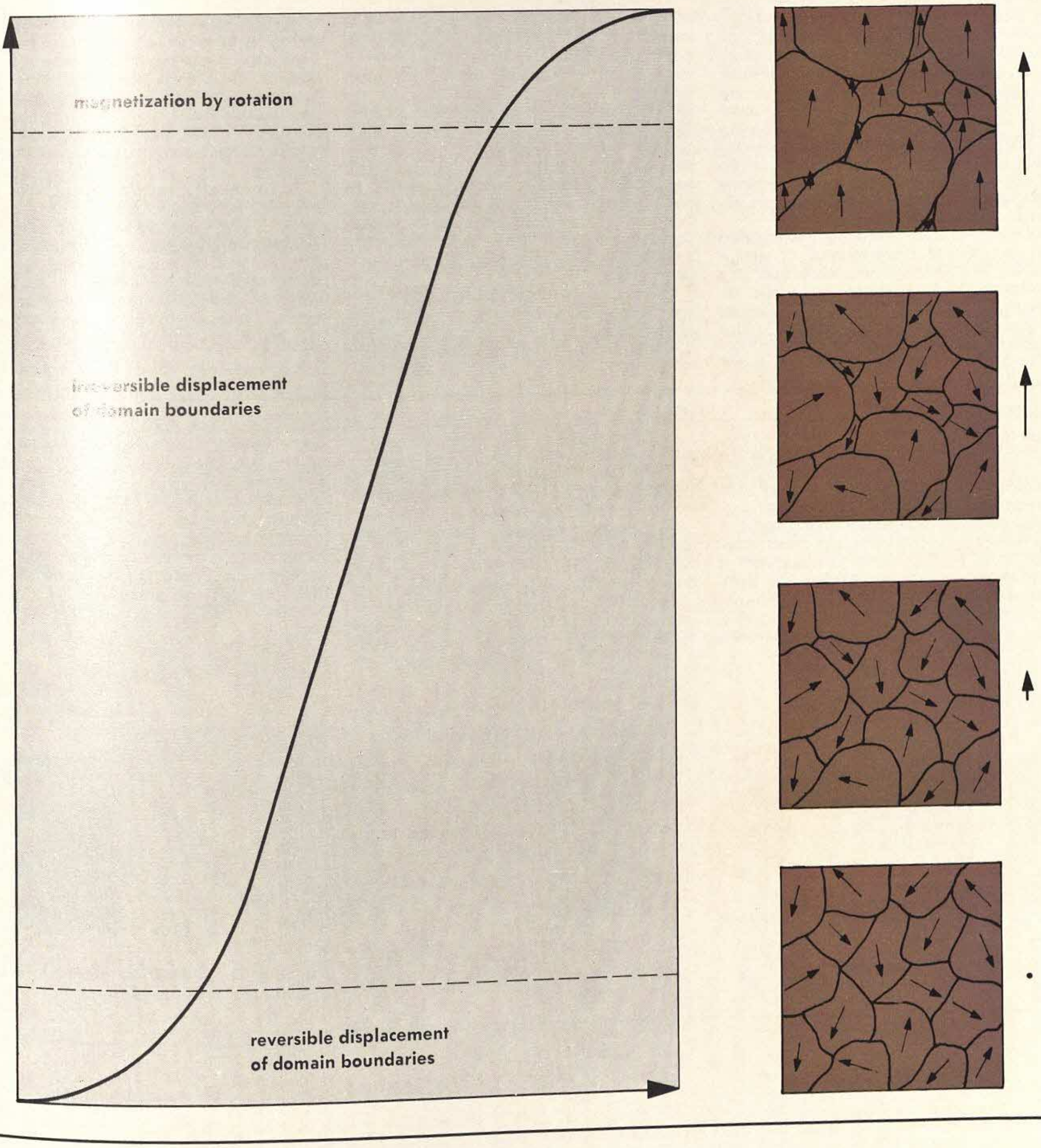
On the left of the illustration is the magnetization curve of a specimen of ferromagnetic substance. This substance does not have a residual field initially, but has been placed inside a solenoid that is capable of producing a field of increasing intensity by variation of the current passing through it. The form of the curve may be explained in three different regions: the initial region, the central region, and the saturation region.

The four diagrams on the right of the illustration show what happens within the ferromagnetic substance.

In the initial (bottom) region of the curve, magnetization is the result of displacement of the domain boundaries. This displacement leads to a magnetization that has the characteristic of being reversible. When the inducing field is removed, the demagnetization curve will be almost exactly the same as the magnetization curve.

In the central region of the curve, magnetization is the result of an irreversible displacement of the domain boundaries. The dimensions of the domains grow as the intensity of the inducing field increases. The domains will eventually reach a size where—for crystallographic reasons—they are prevented from further growth, but a rotation of the directions of their magnetization can still occur, producing an increase in the total magnetization. This last effect is modest when compared with the others and magnetization of the substance in the saturation region increases only slightly, as shown by the flatter curve in this region.

Because of the irreversibility of the processes occurring in the central and saturation regions, demagnetization (decreasing the magnetic field or applying one in the opposite direction) will occur along a different curve than that shown for magnetization. This phenomenon is known as hysteresis.



4

THE OBSERVATION OF FERROMAGNETIC DOMAINS—The observation of domains within ferromagnetic substances is based on the use of magnetic powder (magnetite) ground so fine as to form a colloidal suspension. The surface of a ferromagnetic crystal is first smoothed and then covered with this substance so that a thin layer of powder will adhere to the crystal. The grains of magnetite concentrate in the vicinity of the domain boundaries, making it possible to observe these boundaries with the aid of a low-power optical microscope.

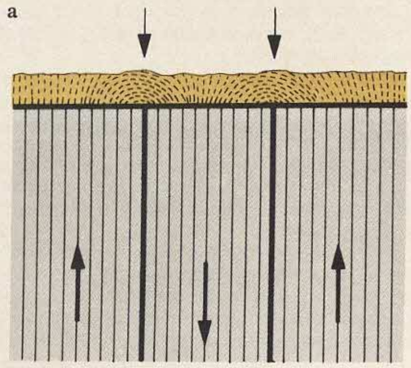
Illustration 4a shows a section of such a crystal, covered with the colloid. The grains of magnetite are seen as they arrange in the vicinities of the poles. The difference in coloration apparent to an observer is a result of this orientation of the grains from the horizontal to vertical position.

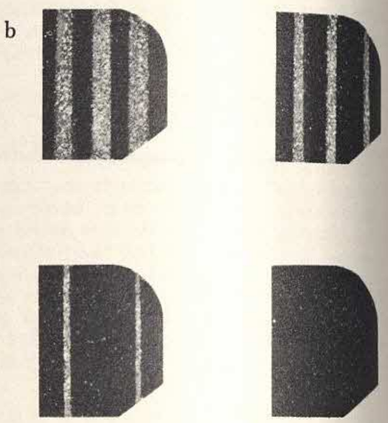
In Illustration 4b the same effect is shown, this time with the assistance of polarized light. The light is sensitive to the orientations of the grains, assisting definition of their position. The light-colored areas correspond to one position of the grains; the dark areas correspond to the opposite position. The sequence of pictures in Illustration 4b demonstrates the growth of dark areas at the expense of the light areas, corresponding to the displacement of domain boundaries in the substance observed.

Such observations permit the interpretation and prediction of characteristics of various materials. For example, the production of a material with high permeability would require that the domain boundaries be mobile and that they not encounter obstacles to their movement. Obstacles could result from crystalline defects, impurities, vacancies, or from interstitial atoms. Furthermore, the crystalline grains of a highly permeable substance must be as large as possible so that the grain boundaries are few and far removed from the domain boundaries. Substances such as pure iron or wrought iron are very permeable. Such substances cannot have a strong residual field because their domain boundaries are mobile and easily magnetized, permitting mobility in the opposite sense to that of magnetization; they lose their residual field as easily as they can be magnetized. This characteristic is a desirable property in the laminations used in transformers.

To produce a substance with a high coercive force, it is necessary to ensure that the domain boundaries within that substance find it difficult to move. Various methods are used to obtain this desired characteristic. One method is to make up the material from very finely ground powder. The domain in such a material will not be able to pass the grain boundaries as it grows. Another method is to add suitable alloying materials to make the substance impure and heterogeneous. Alnico V is an example of the product of such modern methods.

Similar results were obtained in the past by empirical means, although the coercive forces in the materials produced were much smaller than those obtained by modern means. The outstanding example is steel (iron rendered impure by the addition of carbon or other alloying materials), quenched and tempered to reduce the dimensions of its crystalline grains.





5

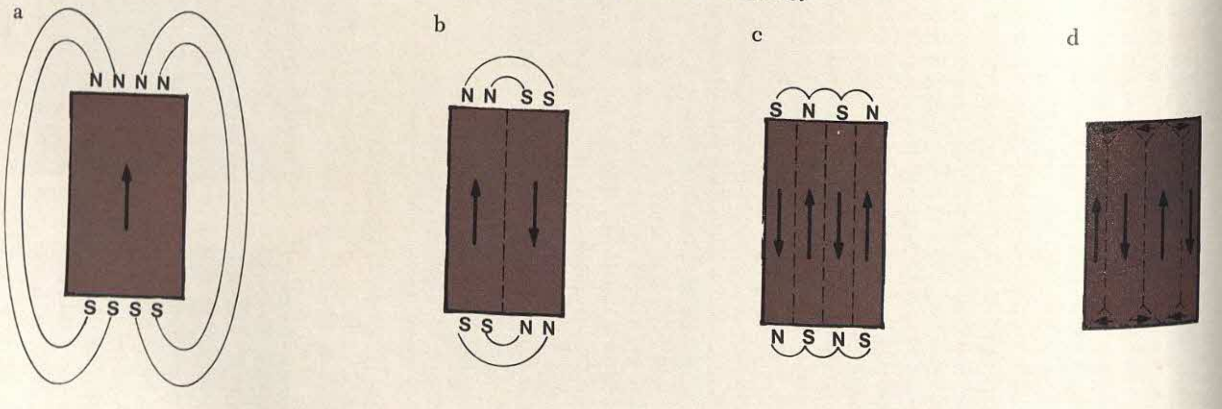
THE ENERGY BALANCE OF THE DOMAINS—Any understanding of crystalline domains is incomplete unless their important energy characteristic is considered.

Illustration 5a represents a monocrystal of ferromagnetic material that has been magnetized to saturation by an external field. It has become a magnet, and the flux lines of its field are demonstrated in the figure. The energy of the magnetic field in this situation is very high; if two domains were formed with their fields antiparallel (parallel and opposite), as shown in Illustration 5b, a reduction of energy would take place. The process can, therefore, occur spontaneously.

It is possible to have an even finer subdivision, such as shown in Illustration 5c. When this occurs a considerable further decrease of total energy takes place.

The formation of even more fractionated domains, such as those arranged in Illustration 5d, permits even further diminution of energy—an arrangement that is found in practice.

The phenomenon of residual magnetization, and the possibility of producing permanent magnets, therefore depend on the crystalline structure and the imperfections of the crystal. Control of the mobility of domain boundaries is the basis of the entire phenomenon and suggests the technical procedures for producing substances that will have the desired properties.



THE MOVEMENTS OF ELECTRONS IN METALS

electric current is a flow of electrons

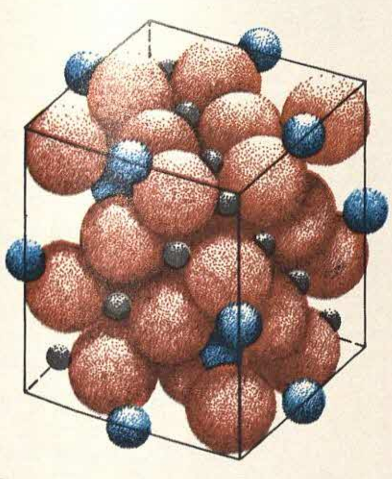
Simply stated, the question here is: How are electrons emancipated? Electrons, those minute particles found in all matter, are bound to atoms; therefore, they are not generally free. Yet free electrons are needed in a great number of physics experiments and, indeed, in many practical applications as well. This article discusses how electrons can be extracted from matter, and how they can be made to move at will.

CONDUCTORS AND INSULATORS

Solid bodies can be divided into conductors and insulators. Although this is not an all-encompassing statement, since it does not cover all existing bodies, it is sufficient for this investigation.

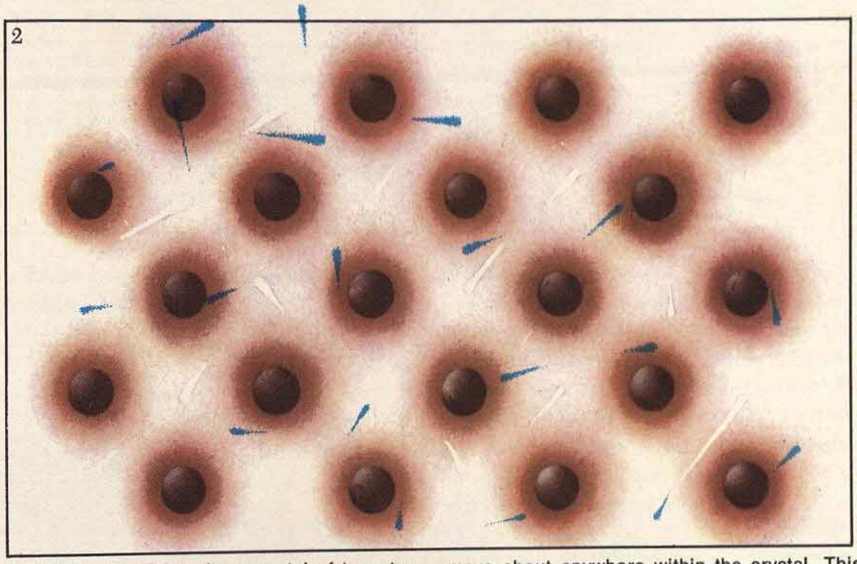
In an insulator the atoms are arranged in various ways to form a crystal lattice. At times they are arranged in a rather complicated manner, as in Illustration 1, which represents the crystalline structure of spinel, $MgAl_2O_4$. Regardless of how the atoms may be arranged, however, the one fact common to all insulators is that the electrons are all firmly attached to their respective atoms. Each sphere in the illustration represents an atom complete with all its electrons, and these electrons are all closely bound to the atom itself.

1



THE STRUCTURE OF SPINEL—Each sphere represents an atom with all its electrons firmly attached.

2



A METAL SECTION—In a crystal of tungsten, about one electron per atom remains free to move about anywhere within the crystal. This characteristic is common to all metals.

The situation is quite different in the crystal of a conductor such as metal. In Illustration 2, which shows the crystalline structure of tungsten, the brown spheres represent the atoms of the metal. Illustration 3 shows how these atoms are arranged in space: they occur at the corners of a cube with an additional atom at the center. If a crystal of tungsten were cut along a plane parallel to one of the faces of the cube, the atoms at the corners of the cube could be seen, as well as, on a somewhat lower plane, the atom at the center of the cube.

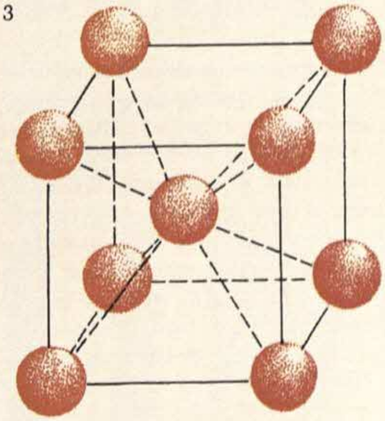
The important point is that not all the electrons of each atom remain bound to the atom when this crystal lattice is formed. Approximately one electron per atom remains free to move about the crystal lattice. This is why Illustration 2 shows electrons (blue figures) placed between the atoms and moving about in the interstices of the crystal. This image is not perfect from a theoretical point of view, but it does give an idea of how the electrons are arranged inside a metallic crystal.

HOW ELECTRONS BEHAVE INSIDE A METAL

Since there are freely moving electrons inside a piece of metal, the next question is: what are their movements? If no electric field disturbs them, these electrons will find themselves in a random equilibrium inside the crystal; in other words, they will not have a preferred direction of movement. However, under ordinary temperature it can be seen that the atoms are not perfectly at rest in their positions, as shown in Illustration 2. Rather, they oscillate about their positions, and each moves in a different direction and at a

THE LATTICE OF A TUNGSTEN CRYSTAL—The atoms of tungsten are arranged at the corners of a cube, with an additional atom at the center.

3



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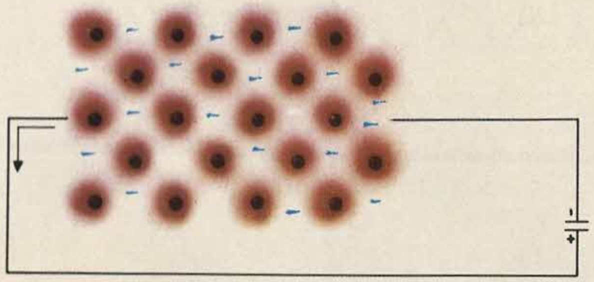

CURRENT AND THE FLOW OF ELECTRONS—An electric field causes free electrons to flow within a metal.

different amplitude of vibration. The oscillations do not have much amplitude at low temperatures. However, this amplitude increases as the temperature rises, for then the atoms will be able to move farther apart as the bonds that hold them together are gradually destroyed; in other words, the metal fuses. The electrons that were moving about among the atoms now collide with them; the energy they receive from these collisions is then passed on to a neighbor during the next collision.

THE THERMAL AND ELECTRIC CONDUCTIVITY OF METALS

If one face of a metallic crystal is heated, the atoms that form this face (or are close to it) are put into a state of agitation. The vibration of these atoms is then transmitted to their neighbors.

In a metallic crystal, the electrons that are free to move will act as a means of rapidly propagating the heat. They will receive impacts from the fast atoms and will then transmit this impact to the atoms that are still moving slowly. The possibility of the heat's being conducted thus depends on the presence of free electrons in the crystal, which, incidentally, explains why metals have good thermal conductivity.

If a difference of electric potential is applied to the opposite face of a crystal, the electrons are attracted to the positive pole and repelled by the negative one. These electrons or, more precisely, a small number of them, will move from one pole to the other. They will enter one of the two conductors that connect them to the voltage generator; they will flow through this conductor and then return to the piece of metal through the other conductor (Illustration 4).

THE "SURFACE BARRIER"

Illustration 5 shows the forces bearing on an electron inside a piece of metal. The atoms that make up the metal are neutral, for they carry within themselves an equal number of positive and negative charges. The latter are electrons. If one electron is removed from an atom, an ion with a positive charge attracting the electron is formed. However, inside the metal the electron **a** is surrounded on all sides by ions that attract it equally. It therefore finds itself in a state of perfect equilibrium, and even the slightest force applied to it (an external electric field or a push received from a nearby atom) will displace it.

But what happens to an electron b that finds itself at the edge of the crystal? This electron is subject to the at-

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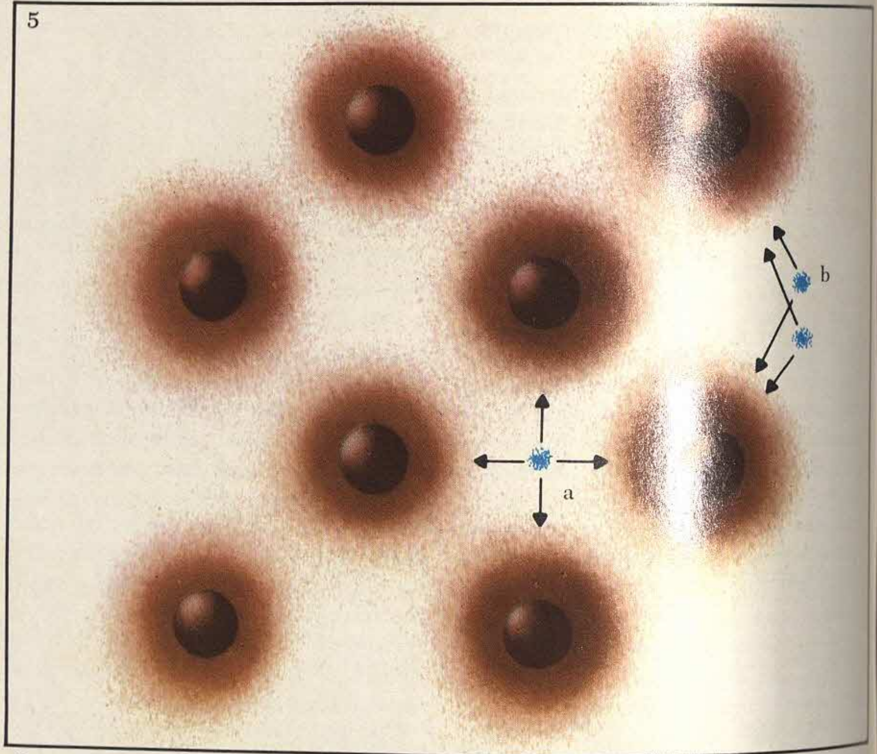
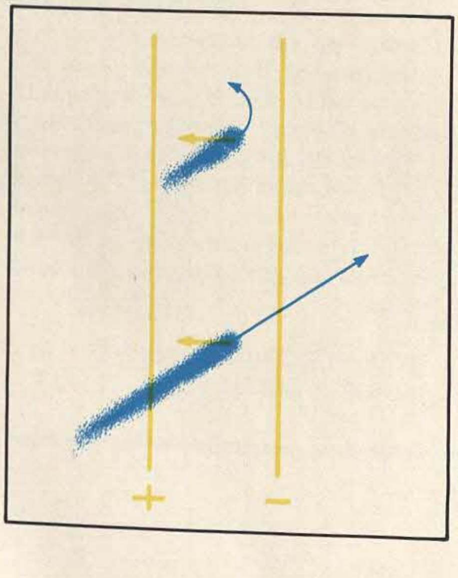


A SURFACE BARRIER—An electron well inside a metallic crystal finds itself attracted uniformly by all the surrounding ions and is, therefore, in a state of equilibrium **a.** On the other hand, an electron at the edge of the crystal **b** is attracted only from the interior of the crystal. Therefore, the electron does not easily escape. The metals, as it were, are surrounded by a "barrier" that electrons find hard to pass through.

6



THE BARRIER THAT KEEPS ELECTRONS INSIDE METAL—Two electrodes produce a potential difference and attract the electrons toward the interior of the crystal. Electrons can escape only if they are very fast.

tractive forces of the nearby ions; these ions, however, are on one side only and no forces are being exerted from the opposite side. The electron is, therefore, subject to an attraction that keeps it inside the crystal.

The surface surrounding any piece of metal thus constitutes a barrier for the electrons, which can be imagined as a pair of electrodes between which the potential accelerates the electrons toward the inside of the metal (Illustration 6). Only if they move from the positive to the negative pole at a sufficient speed can the electrons overcome this barrier. This concept can be clarified by a simple mechanical analogy (Illustration 7). A basin with a flat bottom and slightly inclined walls has minute spheres moving about on the bottom. The only way these spheres can escape the basin is to move with a speed sufficient to propel them over the walls.

THE SPEED OF ELECTRONS

Electrons find themselves in a situation similar to that of the atoms of a gas or the molecules of a liquid that are subject to disorderly movements. The speed distribution of the atoms and molecules is not complicated, and speed distribution curves have a form well known to physicists. When it comes to electrons, however, some rather complex calculations must be made to discover how many electrons move at a certain speed and how many at another. The result of these calculations is the curve shown in Illustration 8; this is the so-called Fermi-Dirac distribution, named after the two physicists who first studied it.

Very few electrons move slowly (curve a). A far greater number have high speeds, although there is a limit. Very fast electrons are almost nonexistent. At low temperatures the curve will be restricted **b**, but it will grow wider when the temperature rises **c**.

This means that some electrons can escape from the piece of metal if the temperature is raised sufficiently. Since the surface barrier varies from metal to metal, the temperature needed to cause the electrons to escape also varies from one metal to another.

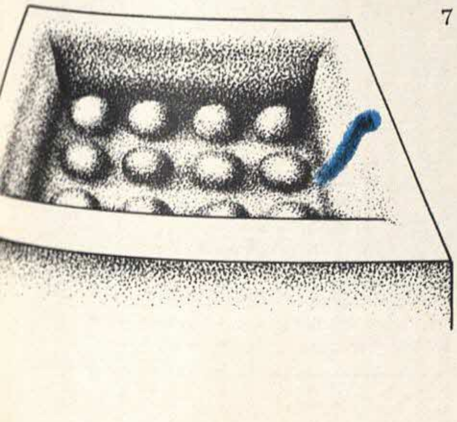
THE EMITTERS OF ELECTRONS

To obtain the emission of electrons from a piece of tungsten, the metal must be heated to at least 1,000° C (1,832° F). The most commonly used tungsten is a wire brought to an even higher temperature, almost 2,000° C (3,632° F). Tungsten as an emitter of electrons is used in vacuum tubes that operate at a high voltage. Since the vacuum is never quite perfect, some gas is always present in these tubes. When the molecules of this gas are struck by the electrons emitted by the filament, they become ions that strike the filament with considerable energy and eventually ruin its surface. Tungsten is one of the materials that have the greatest resistance to this kind of bombardment. The emission of electrons is easily increased. The surface of the tungsten filament need only be covered with a material that has a readily overcome surface barrier. This simple procedure makes it possible to construct a filament that will emit a large number of electrons, even at rather low temperatures. Thorium, a useful material for this procedure, can be applied to the tungsten in the form of an oxide mixed with some carbon; then the filament is heated to about 2,800° C (5,072° F). At this temperature the carbon reduces a monoatomic surface layer of oxide to pure metallic thorium, and this layer of thorium permits a copious escape of electrons (Illustration 9). Another system that permits a rich emission of electrons consists of nickel filaments covered with oxides of strontium and barium.

Two other systems consist of (1) using a filament heated by the passage of an electric current, and (2) causing a metallic surface to be heated by a filament. Two types of these emitters of electrons are shown in Illustrations 10c and 10d. These are used as sources of electrons in vacuum tubes, x-ray tubes, electron microscopes, and particle accelerators.

HOW AN ELECTRON CAN OVERCOME THE BARRIER—The electrons (like the small spheres on the bottom of this basin) can escape, but only if they are moving at an extremely high speed.

7



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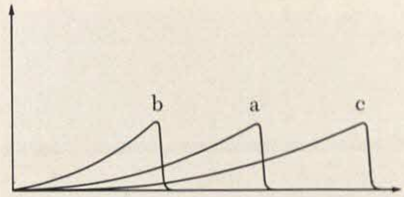
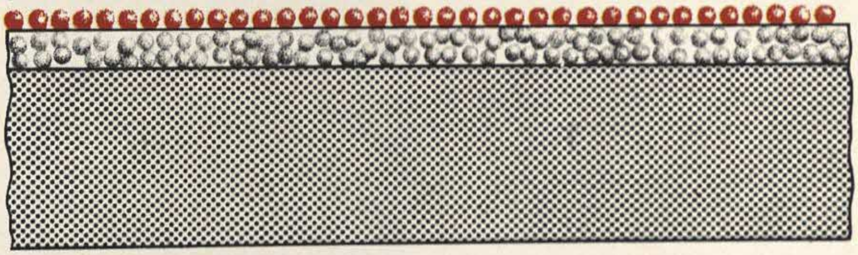


THE SPEED DISTRIBUTION OF THE ELECTRONS WITHIN A METALLIC SOLID—The curve becomes wider at high temperatures.

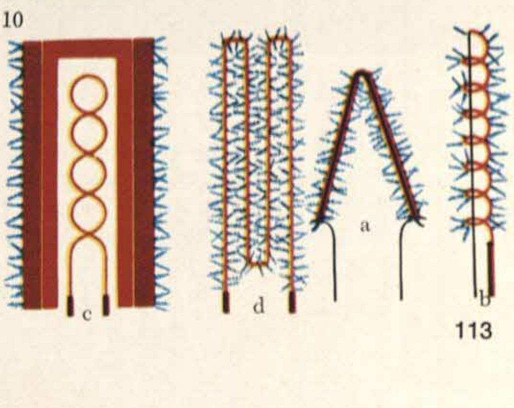
9



THORIUM-PLATED TUNGSTEN—A tungsten filament is covered with a layer of thorium oxide and a monoatomic layer of thorium so that it can emit electrons profusely and even at low temperatures.

ELECTRON EMISSION—The metallic surface of a filament (which can have various shapes **c, d, a, b**) becomes a source of electrons when it is heated.

10



THE ELECTROSTATIC FIELD

the peregrinations of electrons

The electron is one of the basic constituents of all matter. In modern electron theory, matter is made up of atoms that consist mainly of negative particles (electrons), positive particles (protons), and neutral particles (neutrons). Before scientists knew that electric current was a flow of electrons, they defined the direction of current as the direction of imaginary positive charges, and this convention is still used today.

Electrostatics, the branch of physics that deals with phenomena due to attractions or repulsions of electric charges, is believed to have been studied as early as 600 B.C. Indeed, the term *electricity* comes from the amber rod used in those experiments in ancient Greece.

In a normal atom, the charges of the electrons and protons balance, so that when an electron leaves the atom, the atom becomes positively charged; if an electron is added, the atom becomes negatively charged. When these charges interact, an electrostatic field results in which bodies attract or repel one another. This attraction or repulsion is particularly noticeable with small, lightweight bodies such as cork and paper.

ELECTROSTATIC ATTRACTION—When a glass rod is rubbed vigorously with wool, it will attract other light bodies (pieces of paper, for example).

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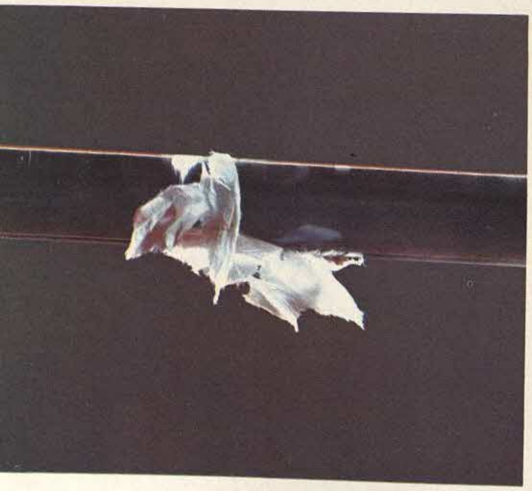
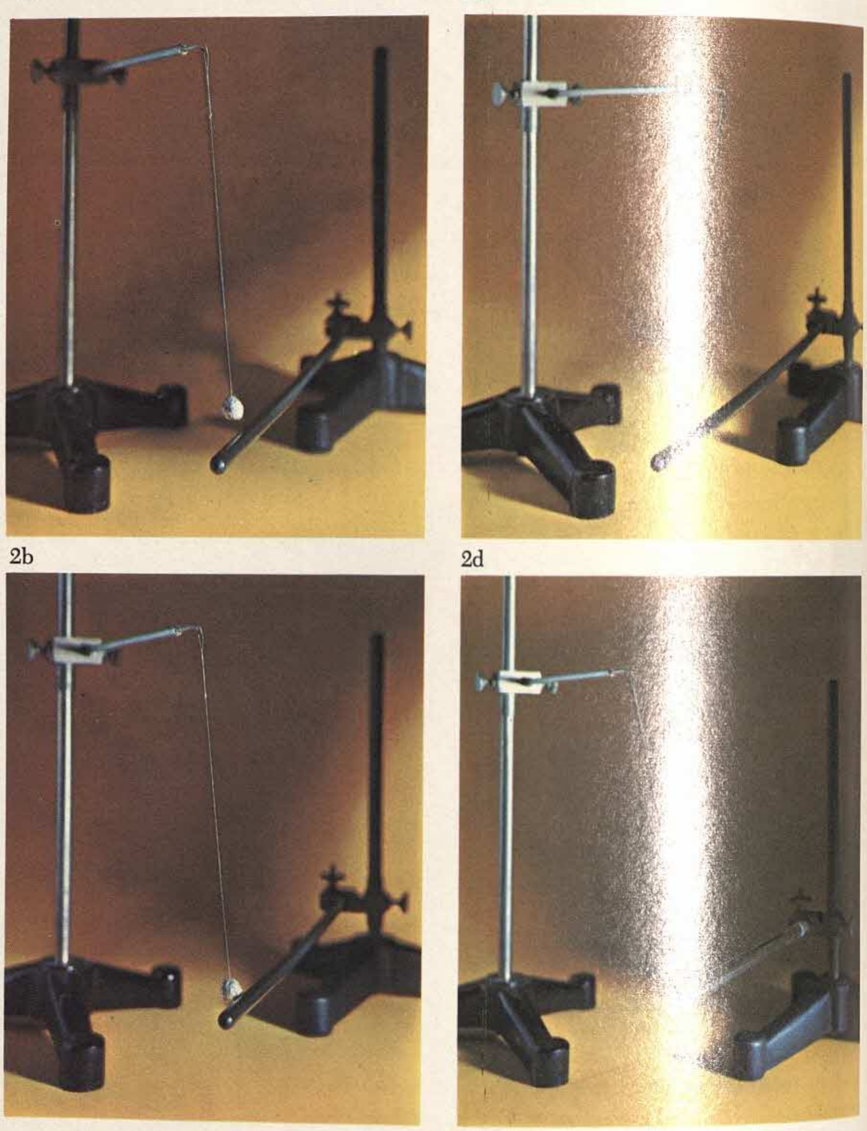


TWO TYPES OF ELECTRICITY

Several simple experiments can be performed to demonstrate the electrostatic field. For example, an ebonite rod rubbed with wool will attract a small ball of



TWO TYPES OF ELECTRICITY—An ebonite rod rubbed with wool attracts a small ball of wool, but when this ball comes into contact with the rod it is repelled. A glass rod will now attract the wool ball.

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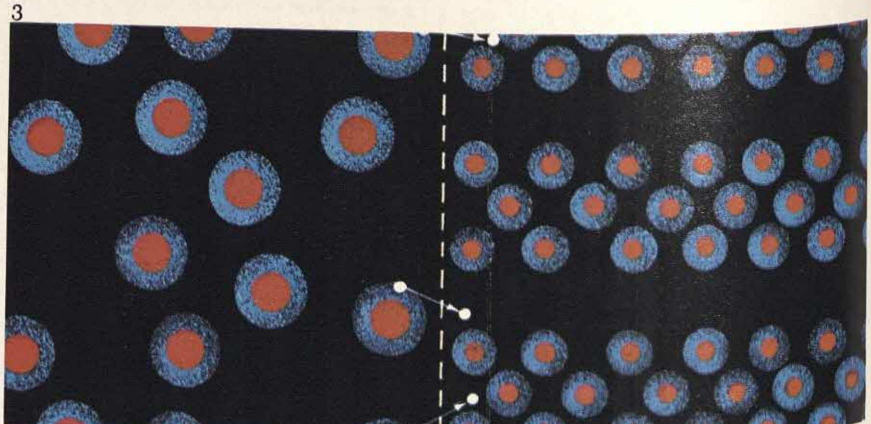
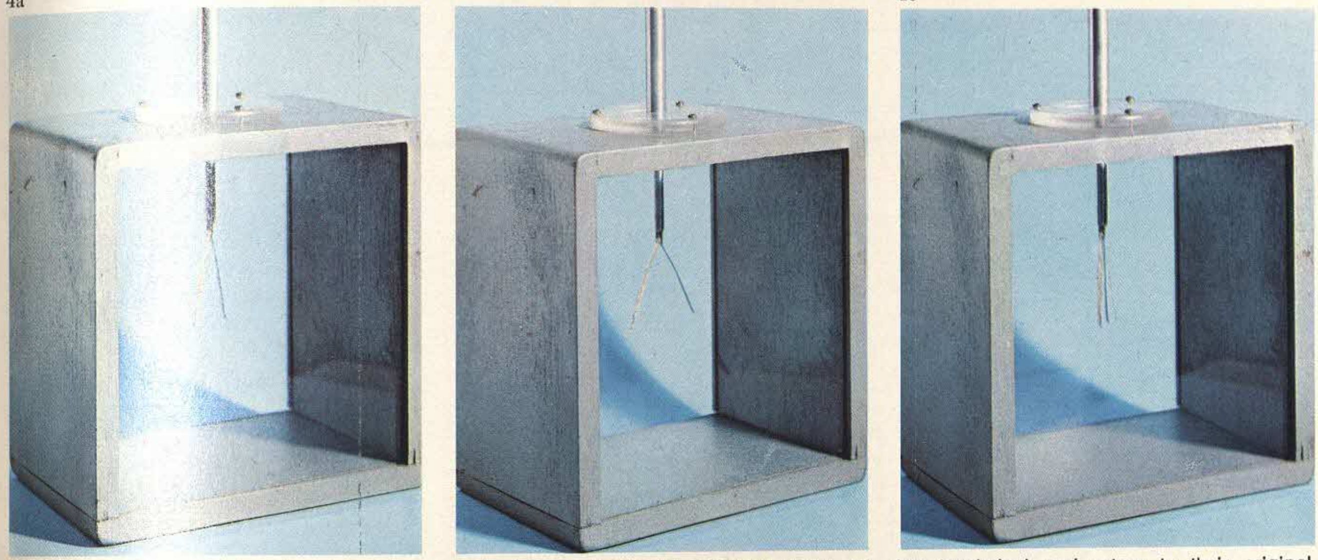


EFFECTS OF RUBBING—When a glass rod (disordered atoms on left) is rubbed vigorously with wool, the outermost electrons become detached and pass onto the wool ball.


4a 4b 4c

ELECTROSCOPE—The foil strips of an electroscope separate as soon as the metal rod contacts an electrically charged body. In time, the foil strips lose their charge (imperfect insulation) and return to their original position.

wool suspended by a silk thread. If the wool ball comes into contact with the rod, however, it will immediately be repelled. The reason for this is that the ebonite rod has an excess of electrons (negative charge) while the wool ball lacks a full complement of necessary electrons and is therefore positively charged. The electrons that are transferred from the wool to the ebonite rod are those most weakly held by the atomic nuclei of the wool.

When the rod and ball make contact, some electrons are transferred back from the ebonite rod to the wool. Around the point of contact, both materials may become negatively charged and the two bodies are then seen to repel each other. This is a basic law of electrostatics. Bodies with the same kind of charge repel each other, while bodies with unlike charges attract.

An instrument often used to detect the presence of electric charges is the electroscope. It consists of two thin foil strips of gold or aluminum protected by an insulated container. Glass windows make it possible to observe the inside of the electroscope. The foil strips connect to a metal rod that passes through a glass or plastic stopper.

When the metal rod is touched with a charged body, the two foils move away from each other because they are charged alike. This separation continues to increase as the charge increases (Illustration 3b). Thus, the electroscope can be used to measure charge quantitatively as well as merely detect electric charges. As can be seen, the foil strips come together when they lose their electric charge.

INSULATING AND CONDUCTING MATERIALS

By touching the rod of a charged electroscope with a piece of grounded copper wire, it can be seen that the foil strips immediately lose their charge and come together. The reason is that the electric charges pass through the copper wire and disperse into the ground. On the other hand, touching the rod with grounded glass or plastic will not cause the foils to come together because these nonmetal materials are nonconductors.

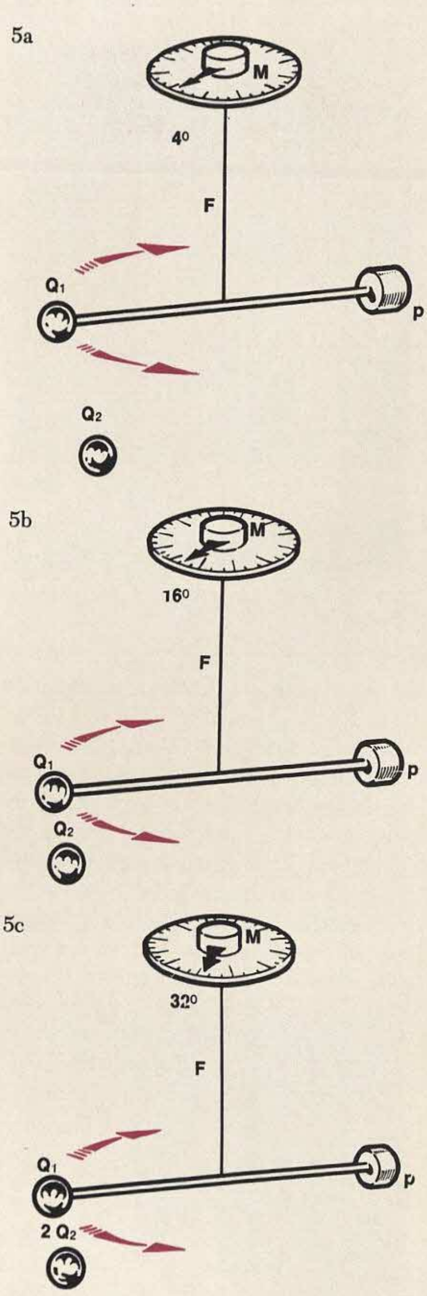
These actions by metals and nonmetals permit a certain classification of materials as either conducting or insulating. Metals, alloys, solutions of acids or bases, and salt solutions are conductors of electric charges. Substances such as amber, glass, porcelain, paraffin, or plastic are considered insulators since they do not transmit electric charge.

When the ebonite rod was rubbed with wool, for example, the electric charges remained at that spot. In a metal rod, these charges would have immediately diffused over the entire surface and been conducted through the body of the person holding it. In the electroscope, the air in the container acts as a partial insulator but a weak one. In time, the charges leak away and the two foil strips unite (lose their charge).

A good conductor contains a large number of free electrons; that is, electrons that revolve in orbits far outside the nucleus and are only weakly attracted to it. Such free electrons are very limited in substances considered insulators, and any transfer of charges becomes most difficult.

COULOMB'S LAW

The charge in a body is usually designated by coulombs (**Q**) and is determined by the difference (positive or negative) between the number of electrons and protons. In the torsion balance (Illustration 5), a small sphere attached to the suspended bar carries a charge of $\mathbf{Q}_1$ while the body **p** at the other end of the bar acts as a counterweight. When a second sphere is placed about 10 cm (about 0.4 in.) from the first one, the charge $\mathbf{Q}_1$ is repelled by $\mathbf{Q}_2$ (the charges are alike). This action of the spheres twists the quartz thread with an amount of torsion proportional to the force exerted on it.



COULOMB'S LAW— The charges Q_1 and Q_2 attract with a force that can be measured by means of the torsion in the suspending thread **F**. This force becomes four times greater if the distance between the two charges is halved, and twice as great if charge Q_2 is doubled.

When a knob (**M** in Illustration 5) is used to twist the thread, the amount of torsion in the opposite direction (4° in the illustration) returns the bar to its original position. By placing the charge Q_2 closer to Q_1 (at 5 cm), a 16° rotation is needed to maintain the original bar position; doubling the charge Q_2 requires a counterrotation of 32°. This can be summarized by the formula:

$$F = K\frac{Q_1 \times Q_2}{r^2}$$

which gives the force exerted between two charges Q_1 and Q_2 at a distance r from each other. This force is proportional to the charges, and if one is doubled the force will also be doubled. The term **K** depends on the properties of the space through which the electrostatic force is being exerted. It can be taken as 1 in the case of empty space, or a vacuum.

THE FIELD OF FORCE

The presence of a charged body modifies the electrical state of the surrounding space. A charge q placed at any point in space is subject to a force **F** that can be calculated with Coulomb's law. The charge q is a "test charge" and is normally taken to be quite small. In general, if a test charge becomes subject to a force F, an electric field exists at that point.

This definition indicates that the electric field is totally independent of the test charge, which merely verifies that it exists. Moreover, it is necessary to distinguish between the force exerted and the intensity of the electric field set up by the charge. A test charge placed in an electric field is attracted or repelled with a force **F**; the intensity **E** is then given by $E = F/q$. Because intensity **E** is a vector, it can only be completely defined when its direction and magnitude are known.

A test charge Q placed in the electric field set up by a charge Q_o and distributed over the surface of a sphere will be attracted if the charges are of opposite sign (Illustration 6). The trajectory of the test charge is called the line of force and is used to determine the direction of the electric field at a point in space, the value of the force **F** being known at any point from Coulomb's law.

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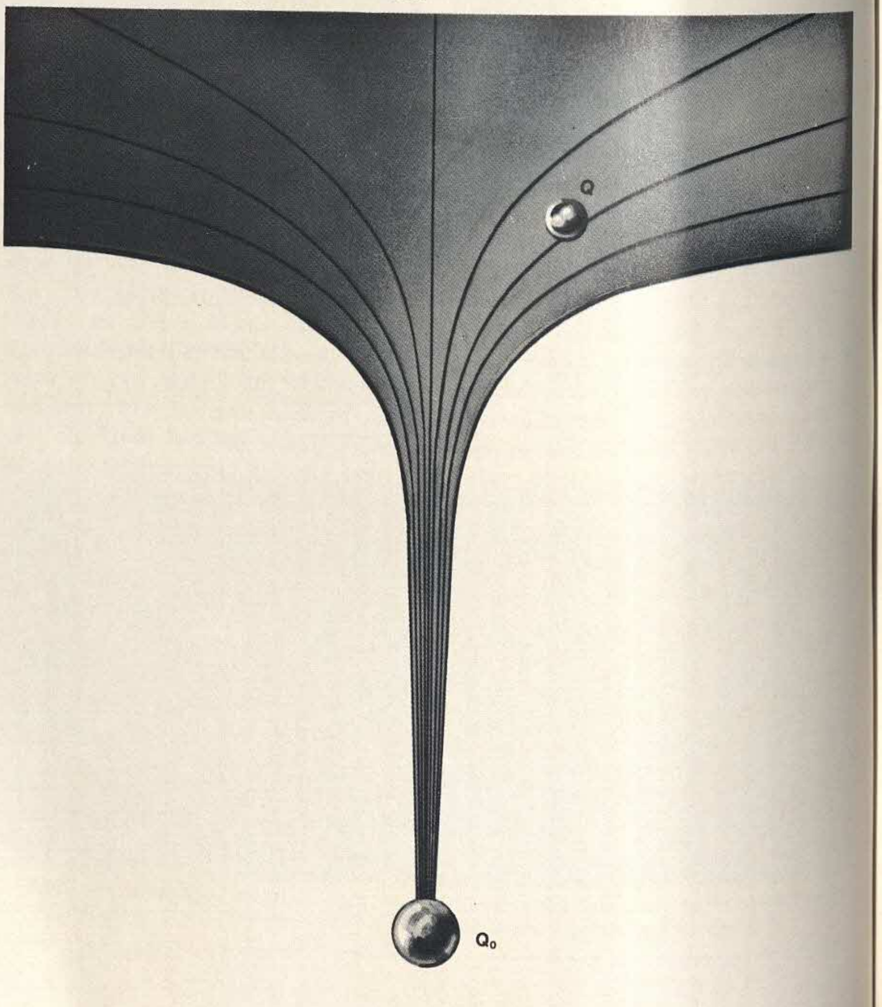
TRAJECTORY AND LINE OF FORCE—A small charge **Q** placed in the field of force of another charge Q_o of opposite sign will be attracted by this second charge in a direction defined by the lines of force.



SOLENOIDS AND ELECTROMAGNETISM

iron rods and copper wires

Magnets are widely used in many branches of science and technology—in large transformers, for example, and particle accelerators. It is possible, however, to experiment with magnets and magnetic circuits with relatively simple equipment. Such experiments show how ferromagnetic substances behave, the general nature of magnetic fields, the forces exerted by magnets, and even how to permanently magnetize a piece of steel. All that is needed is some copper wire and a few pieces of iron and steel. Iron filings can be obtained by filing a soft iron ingot. Other equipment for experiments with magnets and magnetic circuits includes a compass, a cork, a cardboard cylinder, a length of cotton thread, several sheets of paper, and flashlight batteries. The following illustrations explain their use.

IRON FILINGS—The simplest and cheapest material used to demonstrate the existence and pattern of magnetic fields is a supply of iron filings. These can be obtained by filing a piece of soft (ingot) iron held in a vise. The filings are then collected on a clean sheet of paper and are protected from humidity. A small-tooth file is recommended, because the finer the filings, the easier it is to orient them and thus show the pattern of even very weak magnetic fields. The filings, if examined microscopically, have an elongated shape, and will arrange themselves along their lengths in the direction of the lines of force of a magnetic field. The photograph of a sheet of paper with some iron filings on it shows the peculiar pattern of the lines of force produced by a magnet held underneath the paper.

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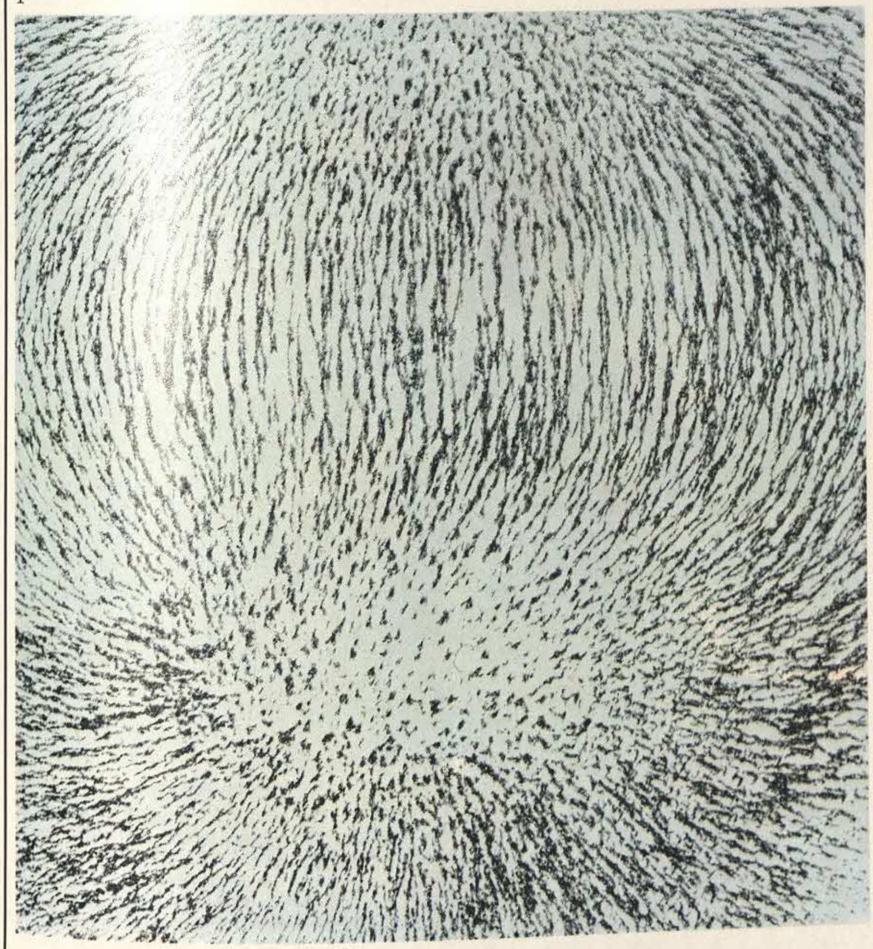

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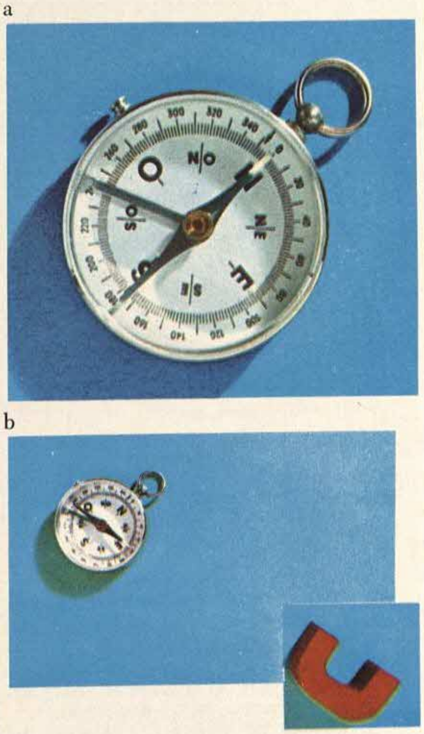
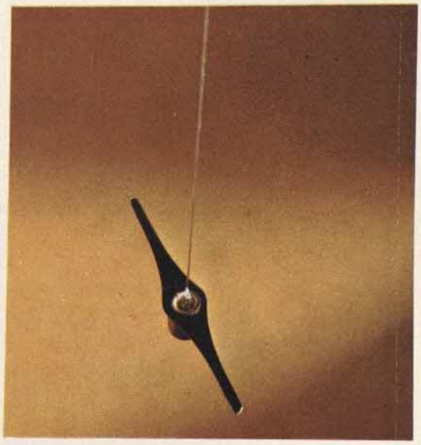


THE NEEDLE OF A COMPASS—The presence of a magnetic field is indicated with even greater sensitivity by a magnetic needle such as that of a compass. A fairly small compass, about the size of the one shown in Illustration 2a, is recommended. The needle is oriented by the Earth's magnetic field; if other magnetic fields exist near the compass, their presence will be indicated by a slight displacement of the needle from the north.

To discover the presence of a magnetic field, the compass is placed on a surface and a permanent magnet (representing an extra magnetic field) is brought within range of the compass. The needle, at first oriented toward the north, is deflected because of the attraction of the nearby magnet (Illustration 2b).

a



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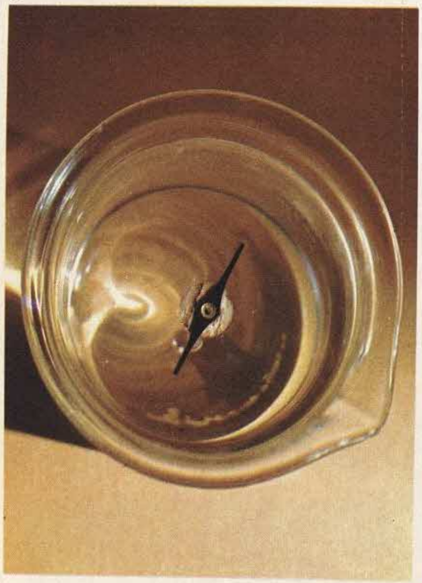

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OTHER MAGNETIC INDICATORS—Although a compass needle is more sensitive than iron filings (with the disadvantage that it does not show directly the patterns of the lines of force of a magnetic field), its size makes it difficult to explore spaces around the equipment.

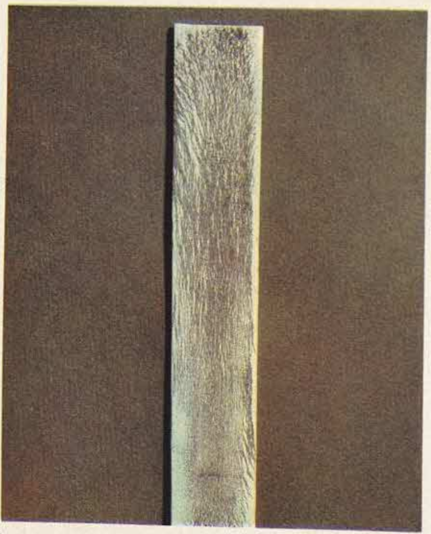
A variant of the compass, based on the same principle but making possible more accurate measurements, can be made by suspending a thin magnetized needle from a very thin glass fiber (Illustration 3a). The more slender the fiber, the more sensitive the capability of detecting magnetic fields. The needle is attached to the fiber by a drop of glue, and is then suspended from a light wooden tripod that is brought close to whatever equipment is to be tested.

Another sensitive indicator of magnetic fields is made by placing a magnetic needle—a compass needle or a permanently magnetized piece of steel wire—on a piece of cork just large enough to hold it, and then floating the cork on water in a container (Illustration 3b). In this case the magnetic field will not only orient the floating needle, but will also attract it, causing it to touch the wall of the container; the resulting friction reduces its sensitivity in orienting itself according to the lines of force.

4

THE MAGNETIC FIELD OF SOLENOIDS—A solenoid is a coil of wire through which an electrical current is flowing. It can be made easily by attaching some insulated copper wire to one end of a cardboard cylinder, tying it with a piece of cotton thread, then winding it around the cylinder in parallel turns until the entire surface is covered (with several layers, if desired). The other end of the wire is attached to the other end of the cylinder. Solenoids are classified according to the number of turns per unit length, and also according to diameter. These photographs show iron filings revealing two patterns of magnetic fields, a very long and narrow solenoid (Illustration 4a) and a very wide and flat one (Illustration 4b).

a



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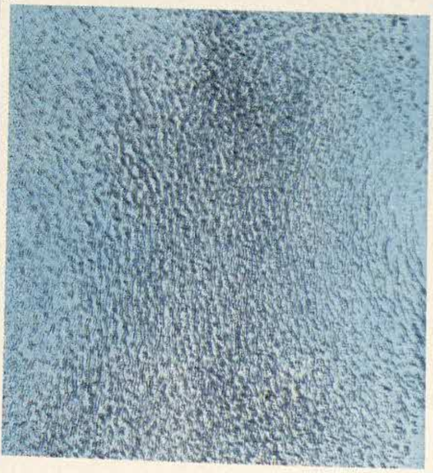

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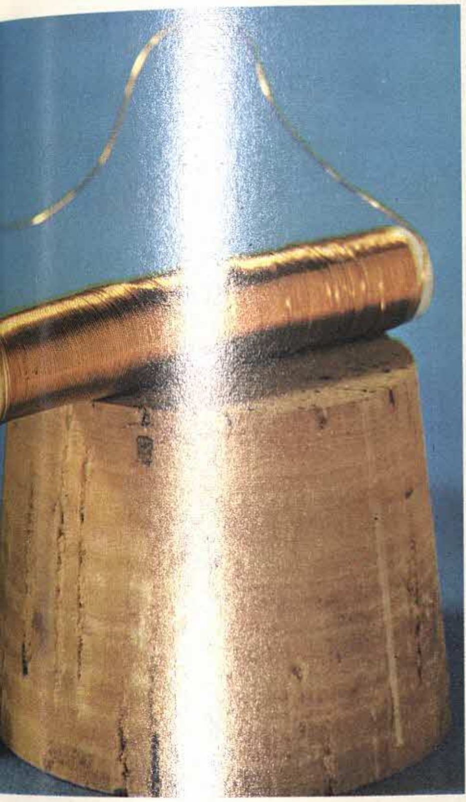
a

b

ELECTROMAGNETS AND REINFORCED FLUX—A simple electromagnet can be made out of a solenoid into which some iron bars have been inserted; such a solenoid (Illustration 5a), once it has been supplied with an electrical current, will attract small iron and steel objects placed near its poles. If the solenoid is filled with iron wire (Illustration 5b), it exerts greater force; the iron reinforces the magnetic flux produced by the current. If a certain current flowing in the coil can lift a piece of



iron weighing 20 g to a certain height, the same copper wire and the same iron, using the same current, can be used to make an electromagnet that can lift a heavier piece of iron. This can be done by bending the iron of the solenoid in the form of a horseshoe (like the familiar horseshoe magnet) and attracting the piece of iron to be lifted by the opposite poles of the coil. By so doing, the experimenter will find that the lifting force has been increased substantially.

MAGNETIZING AN OBJECT—One way to magnetize an object, such as a piece of steel, is by rubbing it. Another way is by the induction of a solenoid. A straight piece of steel rod, about 1 mm (about 0.04 in.) in diameter, can be permanently magnetized by first covering it with a thin layer of paper, then winding several layers of copper wire around it in such a way that each turn is perfectly perpendicular to the axis of the rod. If a current of about 1 ampere is passed briefly through the copper coil, the rod will be permanently magnetized in the direction of its length.

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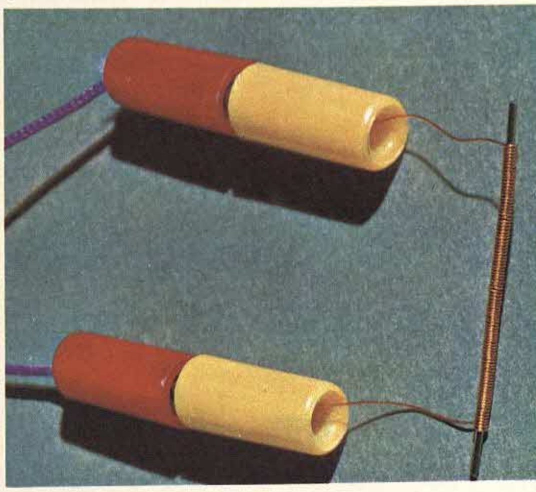

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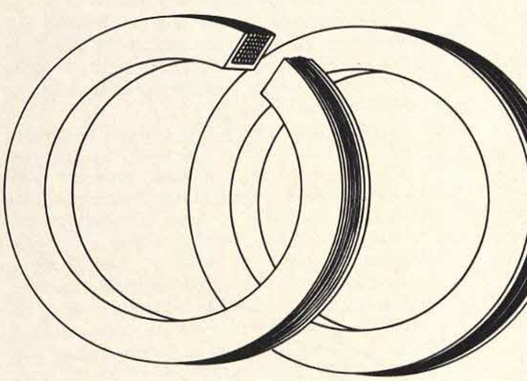

ELIMINATING A MAGNETIC FIELD—Many experiments must be carried out in the absence of disturbing magnetic fields. The magnetic field of the Earth itself can be a disturbance. It can be eliminated by using a pair of solenoids (called Helmholtz coils), constructed as shown in the illustration. The solenoids will produce a magnetic field, the direction of which is parallel to their axis. The current passing through the coils must be varied until a magnetic field is produced of the same magnitude as that of the Earth, but acting in the opposite direction; this can be done by regulating the flow of the current. The terrestrial magnetic field is not always oriented in a horizontal direction, and therefore the coils must be kept inclined if the Earth's magnetic field is to be eliminated. The elimination of the Earth's magnetic field is manifested when a compass needle, placed in the space between the coils, remains in neutral equilibrium—that is, does not become oriented in any particular direction but, if shaken, comes to rest in a random direction, oscillating very slightly.

CURRENT FOR SOLENOIDS AND ELECTROMAGNETS—For the simple experiments just described, batteries will supply the rather moderate voltage necessary for an electromagnet. A 1.5-volt battery of the kind commonly used in a flashlight will supply a current of about 100 milliamperes (0.1 ampere); stronger currents can be obtained by arranging several of these batteries in parallel, as shown, or by using an accumulator.

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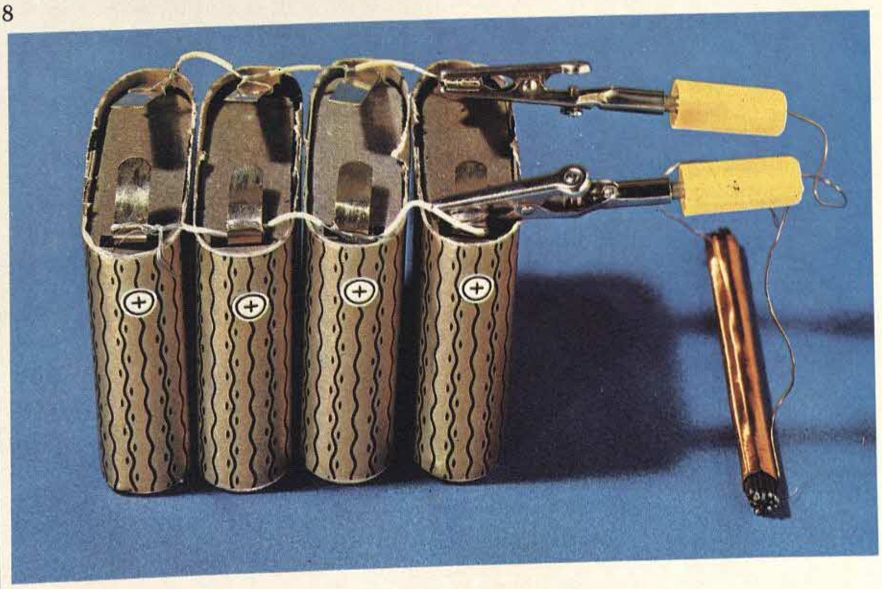

ELECTROSTATIC POTENTIAL

mapping electrical fields

Studying the forces exerted by one electrical charge on another, that is, determining whether a charge is attracted or repelled, is relatively simple from the point of view of electrostatics. However, to solve complex problems in science and technology, it is necessary to know, for example, the force exerted on a charge by an entire surface that is not only electrically charged, but nonuniformly charged as well. Among phenomena governed by forces exerted on charged particles by an electrical field are the motion of a proton expelled from the sun and approaching the Earth; the motion of an electron in a particle accelerator; the motion of ions in an electrical discharge between the insulators of a high-tension line; and the motion of electrons in a vacuum tube.

The solution of such problems, which concerned the most illustrious mathematicians and physicists of the nineteenth century, was facilitated by the introduction of the concept of potential, which might be defined as a summation of the knowledge of the forces that are generated around an electrical charge.

1

FORCE AND POTENTIAL ENERGY—The concept of potential is derived by analogy from the concept of potential energy in relation to work. If a weight of 1 kg is placed at a series of heights 1 m apart above the ground, up to, say, 20 m, and the weight is made to drop, different magnitudes of work will be obtained, depending on the level from which the weight is dropped (Illustration 1a). The quantity of work **P** is calculated by multiplying the weight **p** by the height **h: P = p × h.**

If the space above the surface is divided into horizontal planes 1 m apart, by dropping the weight from each of these, different magnitudes of work are obtained. These positions can also be identified with different magnitudes of potential energy, which are transformed into work as soon as the weight is allowed to fall. The same reasoning applies, by analogy, to electrical charges acting according to Coulomb's law of electrostatics, which states that the force varies directly with the product of the magnitude of the charges, and inversely with the squares of the distance between the charges. If the distribution of electrical charges in space is known, it is possible to calculate, by mathematical relationships, the form and position of surfaces of equal potential. Each such surface corresponds to the same magnitude of potential energy and, therefore, to the same magnitude of obtainable work.

On the basis of lines defining these surfaces of equal potential, it is possible to deduce the forces that will act on a charge moving through the space in question. In the field of gravitational forces described previously, for example, surfaces of equal potential are represented by planes parallel to the surface and equidistant from each other (1 m apart). It is known that a mass of 1 kg falling from one plane to another will release 1 kg-m of energy, and therefore can produce 1 kg-m of work, because the magnitude of work is calculated by the product of the weight by the height. These magnitudes are shown, in Illustration 1b, on each surface.

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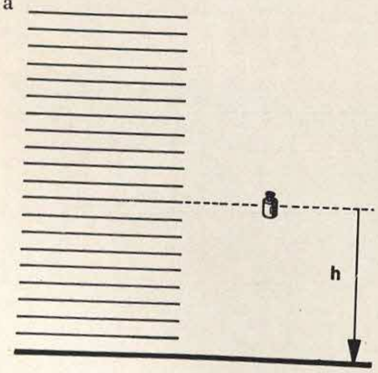

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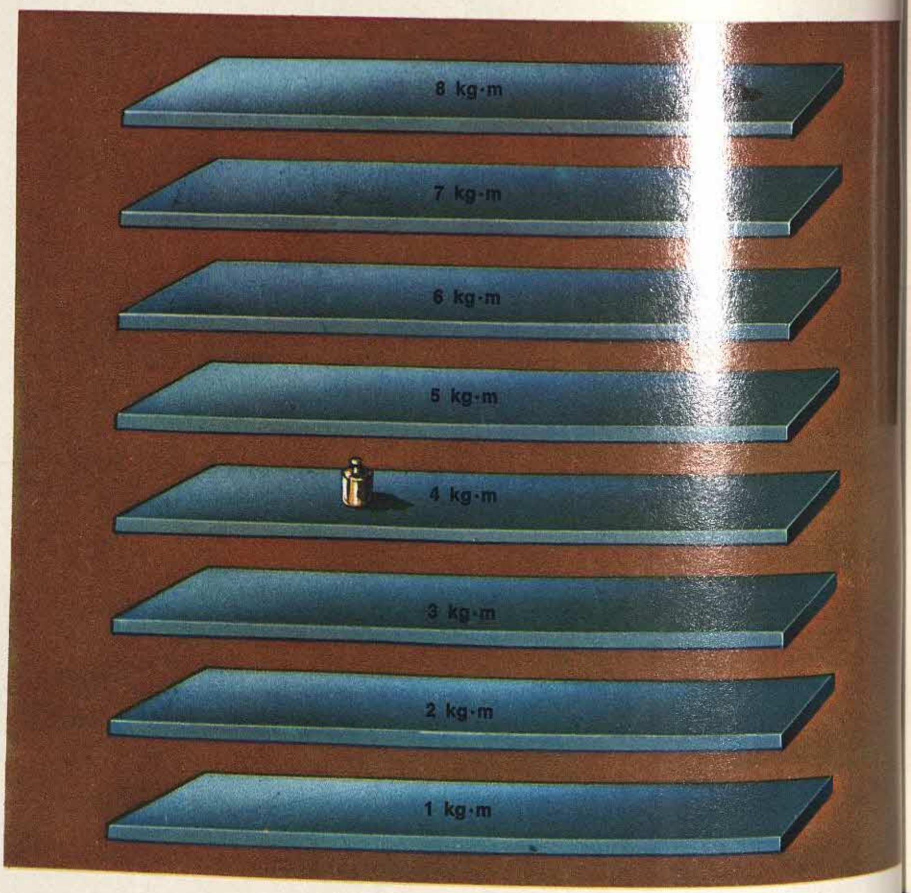

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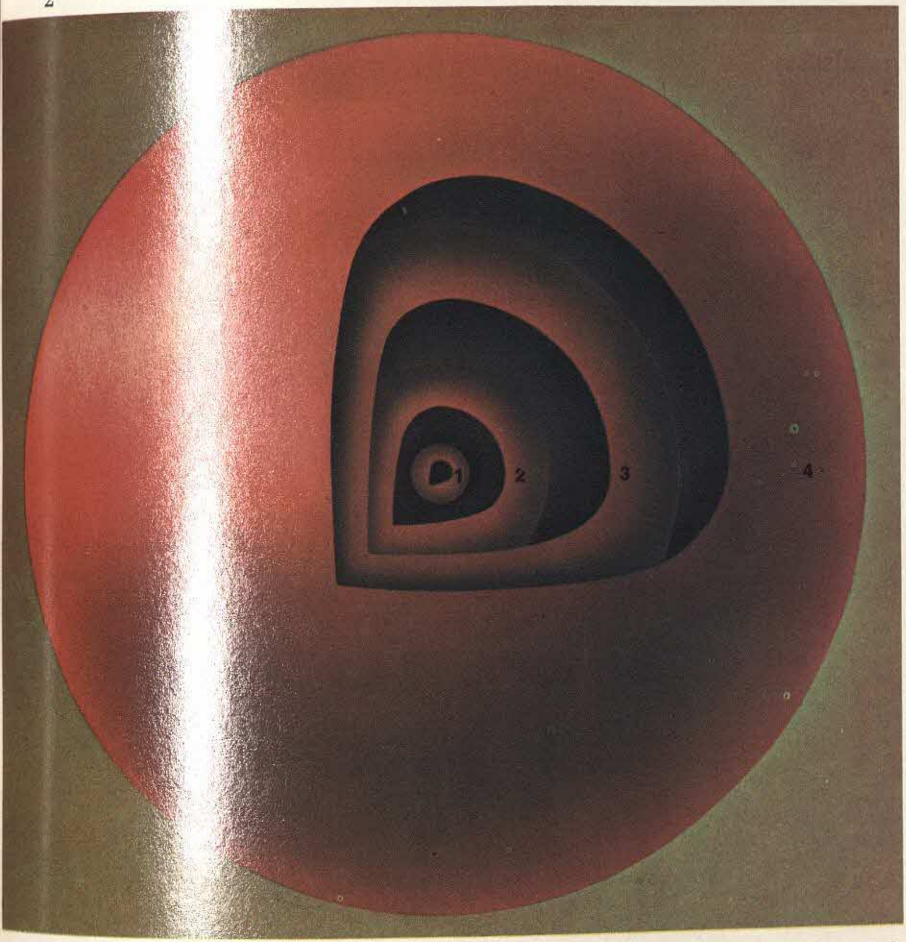


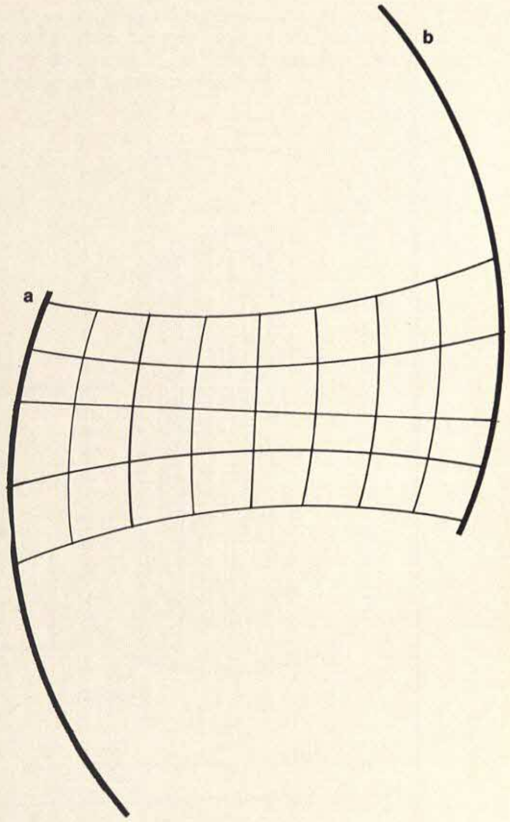
THE POTENTIAL AROUND A SPHERE—If Coulomb's law is applied to two electrons in space, it is apparent that the electrical force will be intense if the charges are close together, but weak if they are far apart. A potential of a charge can be measured, at any given point, by defining the magnitude of work that would have to be performed against the electrical field generated by the charge to carry it from that point to a distance where the reciprocal forces are negligible in magnitude—that is, to infinity.

If an isolated charge in space is plotted so that a field is mapped around it, the parallel and equidistant surfaces corresponding to those in Illustration 1 will take the form of concentric spheres around the charge; however, these spheres, although concentric, will not be equidistant, but will increase in their distance from one another as they are further from the center. If a certain magnitude of energy (1 erg, for example) is to be released by bringing together two unlike charges, the distance between them must be reduced by 2 cm if one of the charges was originally on surface 4, by 1 cm if it was on surface 3, and by 0.5 cm if it was on surface 2. This is the basis for calculating the force, according to the laws of electrostatics: if the force is less intense, the charge must be moved to a greater distance. The equipotential surfaces are closer to one another where the force is more intense, and smaller displacement will perform the same magnitude of work because it will release the same magnitude of potential energy.

DIRICHLET'S PROBLEM—It is not too difficult to calculate the form of the equipotential surfaces that surround electrical point charges. However, when the field generated by a more complex distribution of charges—when, for example, it includes extensive surfaces, each of which can be artificially brought to a suitable potential—the problem becomes more complicated. An example is the situation inside an electron multiplier tube, where a large number of curved platelets are located, each given a suitable potential by means of a voltage generator. When an electron collides violently with one surface **a,** it will knock out three or four other electrons that are intended to collide with the next plate **b.** It is, therefore, necessary for the potential surfaces between the two plates to have a suitable shape, and once this is known, it is possible to determine the most suitable form for the plates. The shape of the potential surfaces between a pair of plates can be calculated mathematically or by using mechanical models. The problem of determining the form of the potential field when the values of the potential at certain boundary points of the area are known is described as Dirichlet's problem, so called after the German mathematician, Peter Gustav Lejeune Dirichlet, who first formulated a law concerning harmonic functions with prescribed boundary lines.

A second case of an electrostatic potential problem also exists, in which flows of current at the boundaries of the field (as in an electrolytic cell) are known. In this case, the calculation is more complex; it is described as Neumann's problem, so called after the German mathematician and physicist Franz Ernst Neumann, who solved it and who also provided the mathematical formulation of the laws of electromagnetic induction.

3



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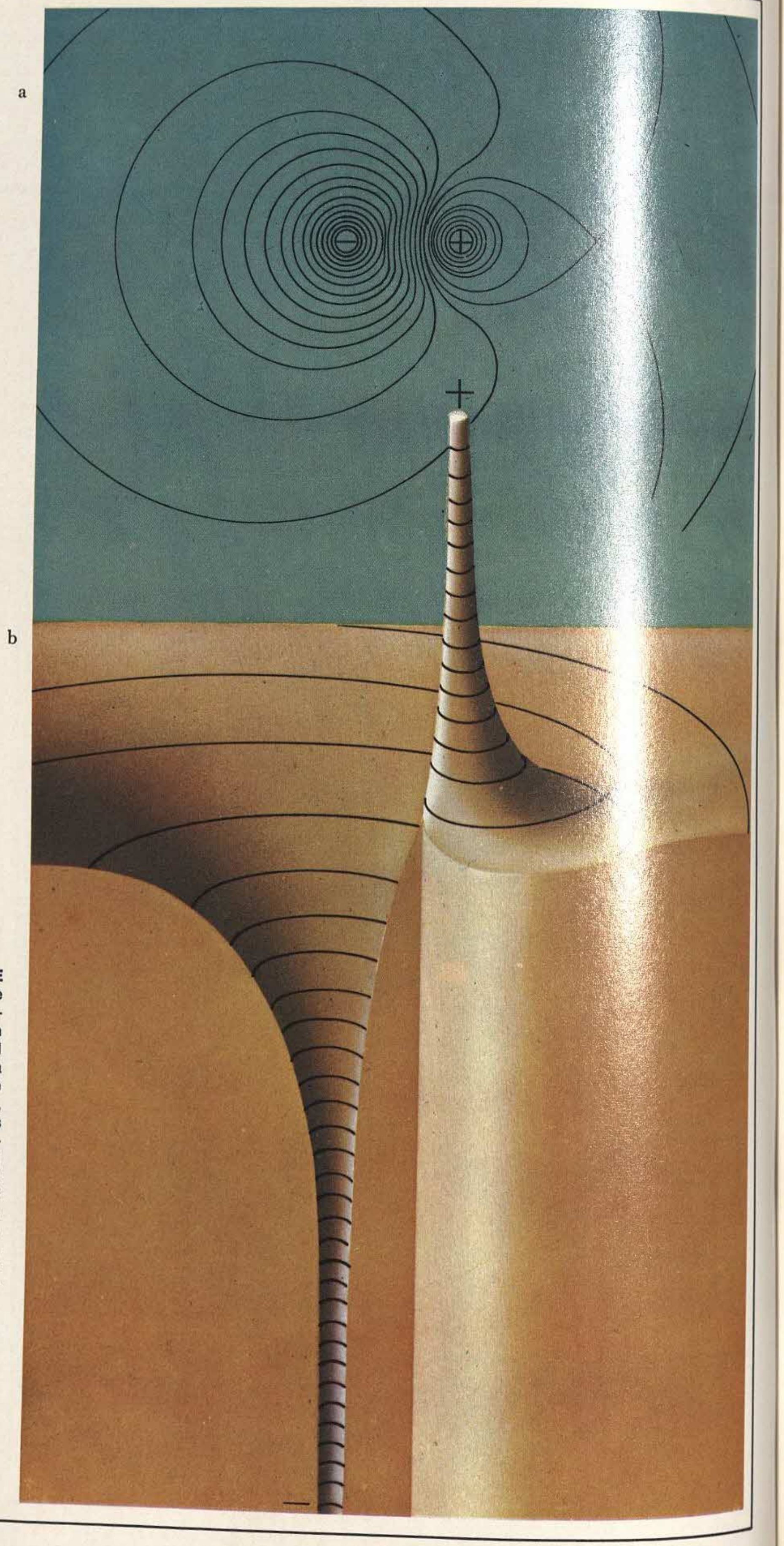

THE POTENTIAL OF THE ELECTRIC DIPOLE —After establishing the analogy between the gravitational and electrostatic fields, it is instructive to imagine the graphic transformation of an electrostatic field into a gravitational field. In Illustration 2 it was shown how a charge opposite to that constituting the source of the potential is attracted to that source, descending from the larger (outer) spheres toward the smaller ones. The concept of descent or falling is proper for the gravitational field; it may be used, by analogy, to describe the electrostatic fields, as if they were relief surfaces. The equipotential surfaces of an electrostatic field, formed by particles with unlike charges and value, are shown in section in Illustration 4a and in stereogram, as contour lines on a relief surface, in Illustration 4b. If a positive unit charge were placed in this field, in order to examine the effects of the field, and if this charge were assumed to be a small, freely moving ball, it would fall straight into the chasm that represents a negative charge and would naturally avoid the peak that represents a positive charge with a much smaller magnitude than the negative charge.

MEASUREMENT OF ELECTRIC POTENTIAL

an application of the analog computer

1

THE CONCRETE PROBLEM — The problem here is to evaluate the potential found between the electrodes of a triode vacuum tube, by using the rheo-electric analog computer. The first step in solving this extremely complex problem is to compare it to the rather simple problem of determining the potential around a sphere or between two flat plates placed opposite each other.

In Illustration 1a, two flat plates are placed parallel to and opposite each other; one of the plates has zero potential, while the other has been brought to a potential of 10 V (volts). The illustration clearly shows that the potential between the two plates forms a simple grid of parallel and equidistant lines. This solution can be easily obtained by using the most elementary laws of electrostatics.

In Illustration 1b, a charged sphere (in section) is set at some point in space. The lines of equal potential around this sphere take the form of concentric circles and can be found through elementary electrostatic calculations.

The simple triode (Illustration 1c) offers a more complex problem. The triode consists of an elongated cathode at the center, a grid formed of vertical wires surrounding the cathode, and a plate (or anode) with a perfectly cylindrical shape. The problem is to find out the movement of the electrons within this triode when, after being emitted by the cathode, the electrons are attracted by the plate and repelled by the grid. The first thing that must be known is the distribution of the potential within the space between the plate and the cathode. With the help of a rheo-electric bath, this problem can be solved.

No matter at what height a horizontal cut is made through the triode in Illustration 1c, the same section and the same situation (Illustration 1d) is always obtained as far as the electric field is concerned (as long as the cut is not too close to the top or bottom of the triode). Therefore, the problem can be solved by studying what happens to the electric field when certain voltages are applied to the electrodes **C, G,** and **A** arranged as shown in the rectangular bath **V.**

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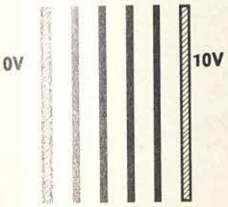

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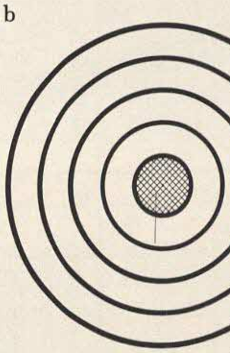
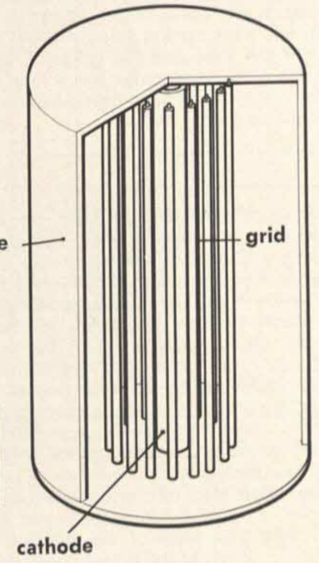


c



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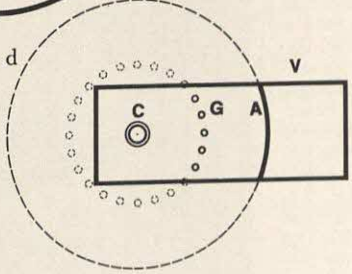

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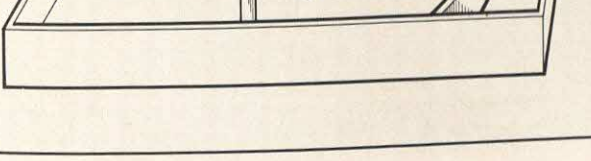
PREPARING THE EXPERIMENT — The apparatus illustrated can be used in cases where the grid has a positive potential with respect to the cathode. To extend the measurements to an experiment where the grid potential is negative, direct current rather than alternating current must be used.

The objective is to know the nature of the electric field between the cathode and the plate of a triode when these electrodes, for example, are brought to the following voltages: cathode 0 V, plate 200 V, grid 5 V. It does not matter if the conditions chosen for a first, easy experiment are not very realistic. In the bath a model of the plate, the cathode, and the grid simulating the real triode are constructed; it is not even necessary that the potential applied to the electrodes be identical to the real one, for it will be sufficient if the values chosen are proportional to the real potential.

To make the best possible use of the bath's area, the plate is extended over the entire width of the bath and reaches almost to the sides (Illustration 2a). The electrodes of the grid must be connected to one another.

The necessary connections are shown. Between the plate and the cathode, 20 volts are applied; between the cathode and the wires of the grid, 0.5 volts. Illustration 2b shows the wiring diagram of the measuring equipment; the terminals of the bridge and the various electrodes must be connected as indicated. The probe will then be displaced in such a way as to effect the measurements at all the points within the bath.

a



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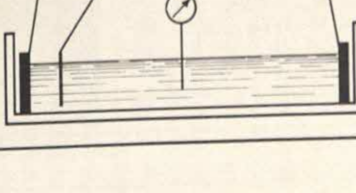


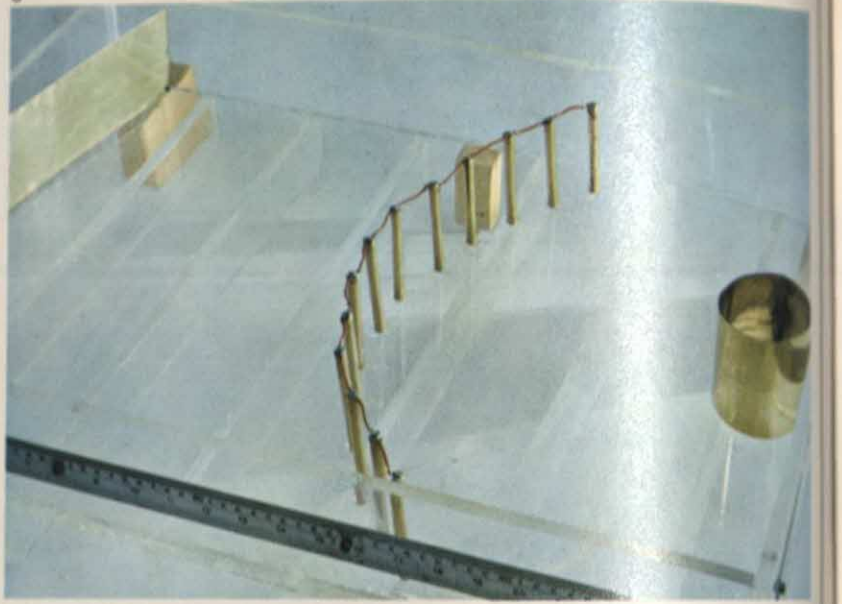
THE CONSTRUCTION OF THE ELECTRODES—The electrodes can now be constructed and fixed in the bath. Actually, the electrodes can be made quite easily from a sheet of brass about 0.4 to 0.5 mm (about 0.016 to 0.02 in.) thick.

The electrodes must be formed according to the dimensions of the design, projecting just a bit above the surface of the liquid. The grid and the cathode can be easily fixed to the bottom of the bath with a few drops of glue. However, the glue must be used as sparingly as possible to avoid displacing water and disturbing the flow of the electricity, thus distorting the measurements.

Great care must be taken in constructing the electrodes. These small cylinders must be set vertically and brought to the same potential. They can be cut from a brass rod of the desired diameter and soldered to a piece of copper wire.

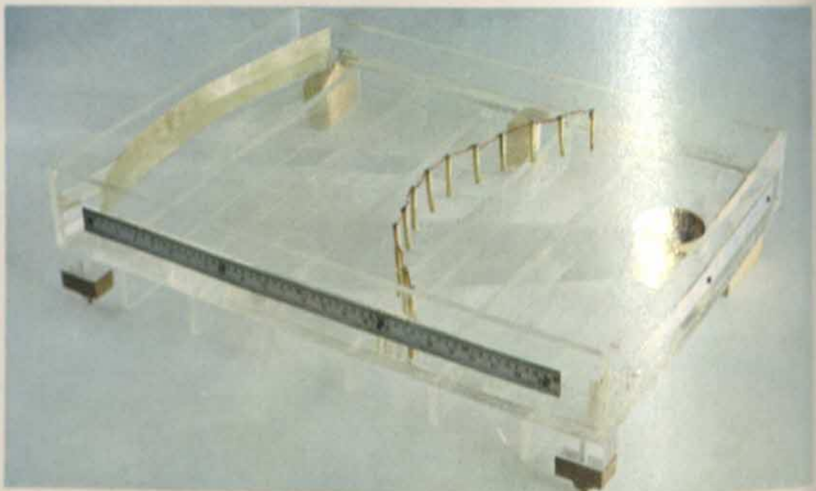
The illustration shows how they should be arranged in the bath and fixed to the bottom. It also shows the soldered joints that hold together the ends of the strips of brass that constitute the plate and the cathode. Care must be taken to grind down the solder to make sure that the electrodes have a constant thickness throughout.

3



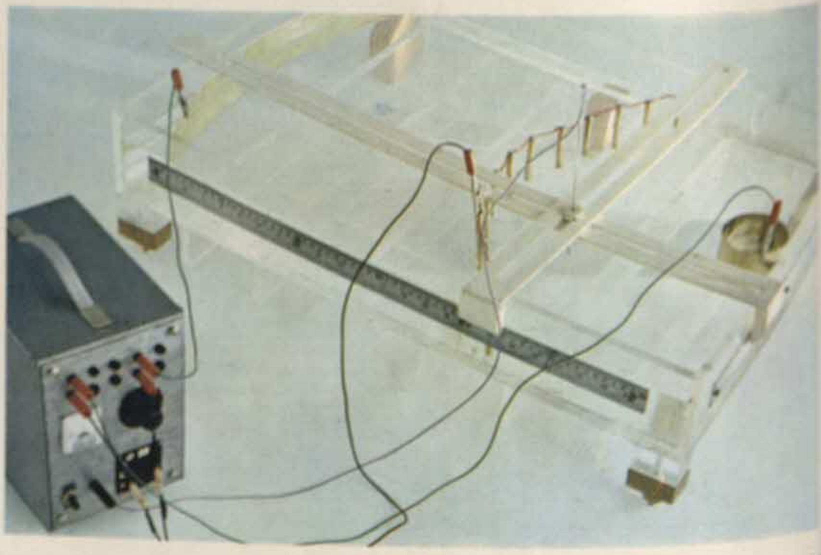
THE ELECTROLYTE—To carry out the measurements, the bath is filled with electrolyte. It is important that the electrolyte ensure a regular flow of current. If the intensity of the current is weak, measurements will be difficult to obtain because the bridge will be unbalanced. On the other hand, if the current is too strong, the transformer may burn out. Distilled water may be used for the bath, and if it gives too weak a current sodium bicarbonate can be added. The electrolyte, perfectly mixed, must be freshly prepared immediately prior to the experiment. An old mixture is subject to evaporation; also, local accumulations of electrolyte will produce irregularities in the electric field. The level of the electrolyte must reach to within about 2 cm (about 0.8 in.) of the top of the electrodes, which of course project above the surface. Since it is vitally important that the depth of the electrolyte be the same at all points, the bath should have been previously leveled.

4



MAKING THE MEASUREMENTS—The field to be explored is limited to the triangular area extending from the cathode to the ends of the plate; irregularities at the edges of the bath are thus avoided. The actual surface of the field does not exceed three-quarters of the bath's total area. A measurement will have to be carried out at every point of a grid composed of squares whose sides are as small as possible. About 2,000 measurements will have to be carried out if the chosen grid squares have a side of one centimeter (0.4 in.). Grid squares with sides 0.5 centimeters (0.2 in.) long also can be chosen; however, although this will ensure greater accuracy, it will call for 8,000 separate measurements. Alternately, if qualitative measurement is sufficient, a large grid size could be used. Each measurement demands the following operations: (1) displace the probe to the desired position, (2) check the graduated scales to make certain the desired position has been obtained, (3) balance the measuring bridge, (4) read the value of the voltage at this point on the potentiometer, (5) record this value on the map. This operation calls for a great deal of patience.

5

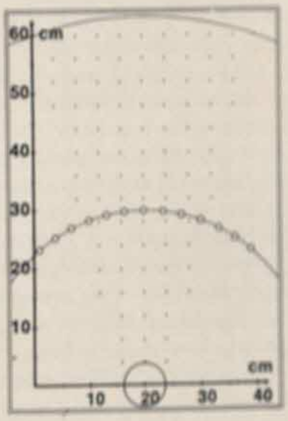


Movie scenes of a ship fighting its way through rough seas are often more realistic than real. They were filmed, more often than not, in a tank with models of ships built to scale. A variation of the movie tank is the test tank used to test the behavior of a ship; this setup, the test tank and the model of the ship, can be called an analog computer of the system under study. Actually, an analog computer can consist of any system that uses a physical phenomenon to simulate the behavior of a system being studied. Analog computers, therefore, can be used to exploit the analogy between certain kinds of natural phenomena (mechanical, hydrostatic, or aerodynamic) and some electrical phenomena. The study of phenomena by means of electric phenomena is quite practical.

A rheo-electric analog computer can be constructed that can simulate the potential that would occur in the air between two electrodes charged to any desired potential; this simulation is achieved by means of the potential established in an electrolytic bath. Thus it is possible to resolve problems in electronic optics and in the insulation of high-tension transmission lines, among others.

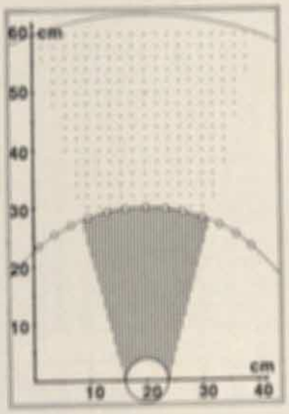
MAPPING THE FIELD—Here is the graph that must be prepared for constructing the map of the field around the electrodes of the triode. The map is constructed, of course, on the basis of the square grid chosen. This graph can be used for tracing a rough map. The electrodes are drawn on a sheet of squared paper. The drawing is then filled with a large number of points, each one corresponding to a pair of coordinates at which a reading is taken. The value of the measurement is written next to each point. At the edge of the sheet are drawn the two coordinate axes, which have the same scales as are to be found on the two slides (60 cm, about 23 in., on the longer slide, and 40 cm, about 15.5 in., on the shorter slide), which make it possible to fix the position of the probe.

6



A MORE EFFICIENT METHOD OF MAPPING—Once the map is obtained and the equipotential lines are constructed, it may seem that too many measurements were taken near the plate, and too few between the cathode and the grid. This immediately suggests that it might be better to space the readings more widely in the neighborhood of the plate, while using a smaller grid between the cathode and the grid. For example, a 2 cm grid might be used near the plate, while the side of the grid square could be reduced to 0.5 cm between the grid and the cathode. Furthermore, it can be expected that the equipotential lines will more or less follow the form of the electrodes; therefore, the measurements can be planned as shown by the layout in the illustration.

7



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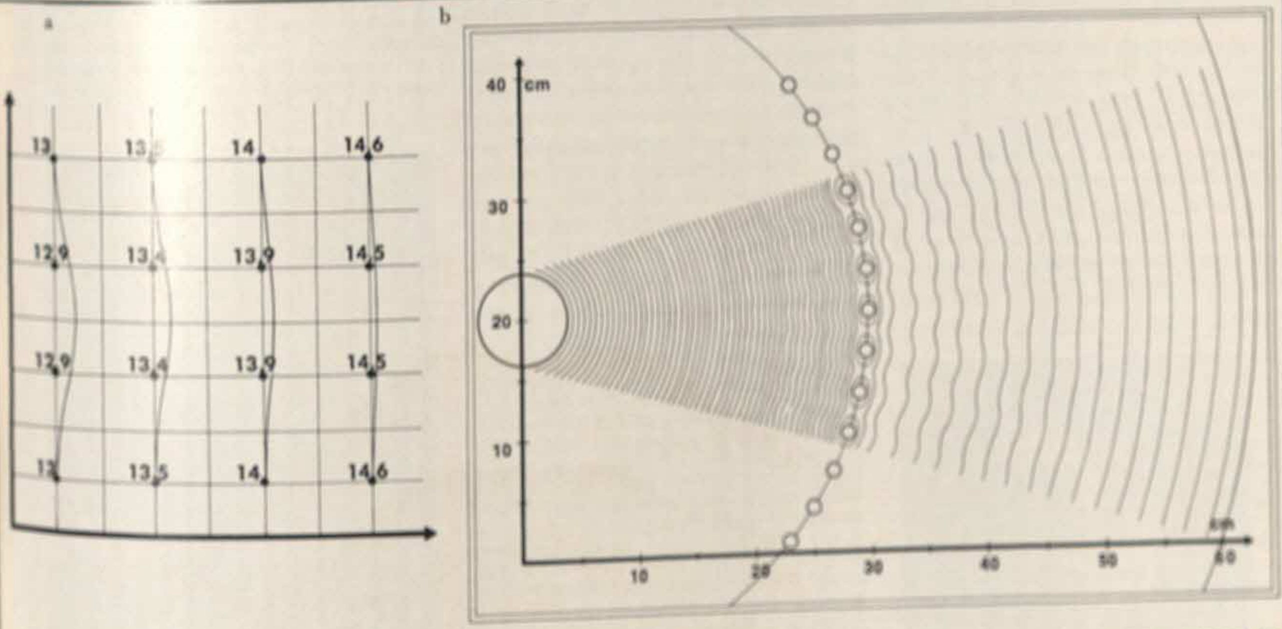

a

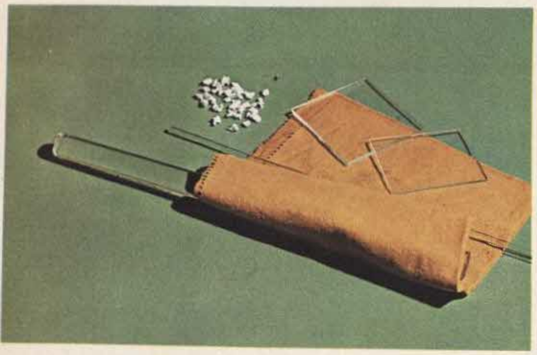
b

OBTAINING THE EQUIPOTENTIAL LINES—The result of all this work will be a numbered grid. Yet the still-sought primary goal is the trend of the equipotential lines of the field around the electrodes. The data, therefore, must be reduced to this form. Illustration 8a shows the principle on which the reduction is based: there are sixteen points, and the value of the measured potential has been written against each of them. The illustration shows the positions of the equipotential lines where the voltage has values of 13, 13.5, 14, and 14.6 volts. To evaluate where these lines pass, an interpolation must be carried out along the sides of the squares.

In the end, after all the interpolations have been carried out (these are very easy and can be made by eye) at all the points of the grid, this map (Illustration 8b) of the potential between the electrodes of the triode is obtained. In the immediate vicinity of the cathode and the plate, the equipotential lines faithfully follow the form of these two electrodes. This technique may also be used to solve hydrodynamic and aerodynamic problems by exploiting the correspondence between these systems and electrical systems.

ELECTROSTATIC PHENOMENA

experiments with charged bodies



MATERIALS—Some of the materials used in an electrostatic experiment are shown here. Rods and sheets with good insulating properties are used. These properties may have been reduced during manufacture, but they may be tested by rubbing the rod or sheet with woolen cloth or fur and then holding the rod or sheet close to small pieces of tissue paper, dry cotton fiber, or very fine sulfur powder; if these materials are attracted by the rod or sheet, the material is suitable for experimental use.

Static electricity is the term used for the phenomena that occur between electrons located on charged bodies; the phenomena result from the position or grouping of the charged bodies, rather than from their movement. The study of these phenomena constitutes a branch of physics known as electrostatics. The phenomena themselves are of great importance in industrial processes. Their study is useful for the more general study of electricity. A few elementary experiments are extremely instructive. Although these experiments are by no means spectacular, they are sometimes difficult to carry out.

ITEMS FOR THE EXPERIMENTS

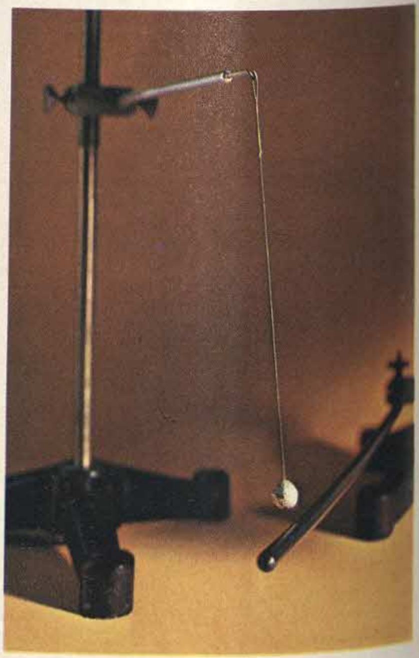
Experiments in electrostatics consist in demonstrating the presence of electric charges on the surface of bodies generally described as nonconductors or insulators, because the protons and electrons of their atoms are so arranged that it is difficult for a flow of electrons (electricity) to take place within the body. Common substances of this kind are glass, sulfur, amber, celluloid, and ebonite.

Such materials are used in electrostatic experiments, in the form of rods or sheets, but only in conditions of perfect purity; their insulating capacity diminishes with the slightest trace of impurity, even a trace invisible to the eye. A glass rod held in a perspiring hand no longer has insulating properties. Thus precautions must be taken to maintain the cleanliness of nonconductors used in these experiments; they must be handled with gloves or other protective material.

Other nonconductors include plastics, such as polyethylene and polyvinyl chloride, which are also obtainable as rods or sheets. When manufactured in the form of continuous sheets, these materials sometimes become contaminated running through the machinery, or electrostatically charged as they rub against the various rollers and supports, and this must be taken into account when they are used in electrostatic experiments. When polyethylene is used for packing bags, in fact, the presence of electrostatic charges prevents the automatic handling of the material and interrupts the continuity of the process. Substances capable of conducting electricity are sometimes spread on the surface of these plastic sheets to prevent an excessive accumulation of electric charges; but these substances are not suitable for use in electrostatic experimentation.

When two objects made of different materials are rubbed together to produce static electricity, electrons move from the surface of one to the surface of the other. The object that gives up electrons becomes positively charged, because it then has more positive than negative charges; and the object that gains electrons becomes negatively charged. A common example is the transfer of electrons from the hair to the comb, charging the comb negatively and the hair positively.

THE CONSTRUCTION OF A PENDULUM—A significant test is provided by the use of an electrostatic pendulum, a light body suspended by a thin length of insulating thread. A body with even a very small charge will either attract or repel this pendulum. The thread can be made of silk, or a thin fiber of some other insulating material; it is suspended from any suitable stand. The pendulum may be a pith ball, a plastic with good insulating properties such as polystyrene, or even cotton; it must be light if it is to be sensitive to weak electrical charges.



EXPERIMENTS INVOLVING THE HUMAN BODY—If a sheet of polyethylene or polyvinyl chloride is rubbed with dry wool or fur, becoming highly charged with static electricity, and is then brought close to the head or the back of the hand, the hair will stand up. The same thing happens when a celluloid comb is used on very clean and dry hair on a windy day, as shown in the photograph. Another interesting experiment involves taking off a dry wool or silk garment. A characteristic crackling will be heard, and if this is done in the dark, violet flashes will appear. These are the results of charges that have accumulated on the garment and are now being discharged in small quantities; the luminosity results from the ionization produced during these discharges.

RADIO WAVES GENERATED BY ELECTROSTATIC PHENOMENA—A sheet of plastic material with good insulating property, rubbed and then crumpled in the hand, will produce electrical discharges strong enough to disturb radio reception in the shortwave band between 10 and 13 m. To demonstrate this, the rubbed plastic must be held near the receiver, which must be sensitive and tuned to these wavelengths.

SUBSTANCES PRODUCING OCCASIONAL STATIC EFFECTS

Some substances have electrostatic properties only when they are dry and must be kept in an environment of low humidity to develop such properties. Wool, which is one of these substances, becomes an excellent nonconductor in dry air and can attain a very high density of surface charge. It is, therefore, suitable for interesting experiments, and is especially suitable when it is desired to obtain free electrical charges by rubbing. Cotton or isolated fibers of cellulose can also develop considerable insulating properties. Among textiles, however, the best nonconductor is natural silk, which is used in many experiments and even in electrostatic devices when such a nonconductor is required. The textile fibers in plastic materials are also excellent nonconductors, usable in electrostatic experiments; but these materials have sometimes been modified by special treatments that enable them to absorb dyes or moisture or give them a pleasing texture; in such cases, materials like these are unsuitable for experimentation.

LIQUIDS AND CONDUCTORS

Liquids can also be used in electrostatic experimentation. Oils, for example, are excellent nonconductors; when sprayed in the air, the droplets provide perfect insulation and are used in electrostatic experimentation. When the American physicist Robert Andrews Millikan established the electrical charge of the electron, he began his experiment in this manner.

Many liquids, however, are conductors. Very pure water is a nonconductor, but it readily dissolves many salts and gases and in this condition it loses its nonconductivity. Even pure water placed in a glass vessel will immediately dissolve enough material from the walls of the container to make it a conductor, although only to a slight degree.

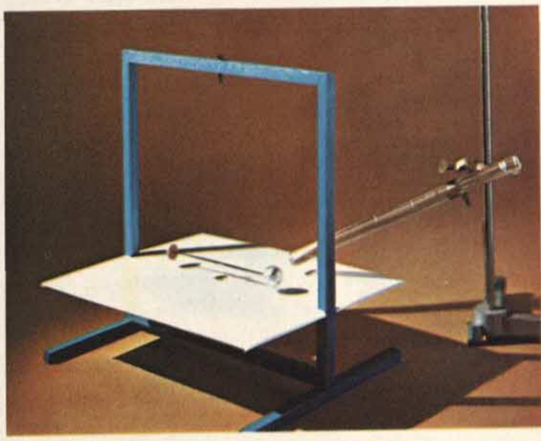
Mercury, like other metals, is an excellent conductor. Drops of mercury in equilibrium on a glass surface, however, cannot discharge because the charges on the surface of the drops cannot pass to the insulator and from the insulator to the ground. Similarly, metal disks can be made that are capable of being charged electrostatically only when they are held by handles made from such nonconductors as polyethylene, ebonite, glass, or amber.

ENVIRONMENTAL PRECAUTIONS

A physicist highly skilled in conducting and demonstrating electrostatic experiments once conducted an experiment before a qualified audience and failed to obtain satisfactory results even though all previous experiments of the type had been successful. The large number of people in the audience had so humidified the air that the materials used in the experiment had lost some of their insulating properties. Care must be taken, therefore, to maintain a low relative humidity wherever electrostatic experiments are to be made.

Humidity may vary from day to day within the same city, depending usually on wind direction. Coastal cities usually have greater average humidity than inland cities; those at low altitudes are usually more humid than those at high elevations.

Relative humidity is usually reduced in the winter by heating a room, unless an open flame is used or water is allowed to evaporate within the room. In general, electrostatic experiments require a relatively dry atmosphere—less than 55 percent relative humidity.



MEASURING CHARGES AND FORCES—A pendulum can be used to measure the intensity of electrostatic forces, if these are sufficiently intense. The weight p of the pendulum must be known with great accuracy. The horizontal force F needed to deflect the pendulum through an angle δ, may be calculated from $F = p \tan \delta$. The angle of deflection of the pendulum can then be measured.

A more accurate and more sensitive method of making this measurement involves the use of a torsion balance. A thin glass fiber is suspended from a stand similar to that used for the pendulum, and is then stretched tight. It supports a horizontal wooden arm with a diameter of about 2 mm (about 0.08 in.), preferably made of balsa or some other light wood. A light sphere, such as that used for the pendulum, is attached to one end of the arm, and a counterweight to the other end. Another stand is needed so that the charged bodies may be brought close to the sphere by means of a horizontal arm. These charges will make the arm deflect through an angle that is proportional to the force exerted by the charged body on the arm of the balance. A torsion balance thus made is rather difficult to calibrate, however, and must be limited to such tasks as measuring the reduction in the attractive force exerted by a body while it is becoming discharged. In this case the charge will dissipate as a small electrical current passing through the stand, and this current can be measured.

ELECTRIC CAPACITANCE AND CAPACITORS

essential elements of an electric circuit

Man's ability to create and harness an electric current began with the discovery that positive and negative charges exist. Like charges repel each other; unlike charges attract each other. This knowledge led to an understanding of the phenomenon called electrostatic induction and consequently to a large number of applications and techniques.

All conductors can be charged. In the simplest terms, this means introducing electric charges—electrons—into a body or subtracting them from it. In the first instance, the result is a negative charge; in the second, the body will be positively charged, since removing negative charges is the same as adding positive ones. How many positive or negative charges can be packed into a body? When electrons are introduced in order to create a negative charge, it is not possible to continue adding electrons indefinitely, or even to the point where the electrons are crowded so close together that no more space is left. The limit is reached much sooner.

One electron repels another in a void or inside a single body such as a metal sphere. If the sphere is electrically neutral, it contains equal numbers of positive charges and electrons and is in a state of equilibrium. If one electron is added, the sphere is negatively charged and is in a condition to repel other negative charges. If more electrons are added, these new charges will remain attached to the sphere while repelling each other and will tend to settle as far from each other as possible. If a second electron is placed on the sphere, the two will settle at the antipodes, or at places directly opposite each other. When a third electron is added, the three electrons will remain on the maximum circumference of the sphere at an angle of 120° to each other; four will be arranged at the vertices of a tetrahedron inscribed in the sphere, and so on. A large number of additional electrons will distribute themselves in such a manner that their density per unit of surface is everywhere equal.

On the surface of any metal body, a force field exists that tends to retain negative charges, so that the electrons do not escape into the space surrounding the metal unless their number becomes excessive. Interesting things occur when the amount of charge on the conductor is very large. When such a conductor is placed in a vacuum, its electrons are projected outward by forces of repulsion that are set up between them. When this conductor is placed in air (or in any other gas), it attracts the free ions that normally exist in the air with such force that they collide with neutral air molecules as they approach the conductor, ionizing them and creating a continuous multiplication of ions. The result is an electric discharge, a spark.

THE COLOSSAL FORCES OF ATTRACTION AND REPULSION

Coulomb's formula gives the force with which electric charges attract or repel each other. Even a very small charge is sufficient to obtain remarkable forces of attraction or repulsion. If, for example, all the electrons present in a gram atom of hydrogen (about 11 liters, or about 671 cubic in., of diatomic gas under normal temperature and pressure conditions) could be detached from the nuclei to which they are attracted, the result would be a positive electric charge (the nuclei) and a negative one (the electrons) each equal to about 96,500 coulombs. If all the electrons of these atoms could be collected at the North Pole of the Earth, and all the nuclei at the South Pole, the two concentrations of charges would attract each other with a force of as much as 58 tons. If the distance between them were shortened from 12,700 km to 1,000 km (from about 7,900

THE CAPACITANCE OF A SPHERE—Taking the radius of a sphere into account, it is possible to calculate the potential that the sphere will attain when charged. The formula expressing the relation between the potential and the radius states that the potential is inversely proportional to the radius:

$$V = \frac{q}{4\pi\epsilon_0 r},$$

when V is the potential attained, q the electric charge, and ϵ_0 a constant called the permittivity of the vacuum (its dielectric constant). The capacitance of a conductor is equal to the ratio between the charge introduced and the potential attained. In the case of a sphere (Illustration 1a), the capacitance C is given by the formula: $C = 4\pi\epsilon_0 r$, which means that the larger the radius of the sphere, the larger the capacitance.

1a

Illustration 1b shows the terminal of a Van de Graaff generator. The spherically shaped conductor (this one has been slightly distorted so that it can be placed inside a cylindrical container) can accumulate an electric charge sufficient to create a field for accelerating subatomic particles. In order to accumulate a sufficiently high charge without increasing the potential too much, such a terminal conductor must be spherical in shape and large in size.

1b

mi to 620 mi), the forces would increase to more than 1,000 tons. At 1 km, the force would be one billion tons (the weight of a cubic kilometer of water). At 1 m (about 3.2 ft), the force of attraction would be one quadrillion tons. Thus, it becomes obvious that such a charge, or even the charge contained in a single gram of hydrogen, could not be collected in a metal conductor of small dimensions.

When an excessive charge is introduced into a neutral metal conductor, the result is an electric field that tends to expel the charge. Also, different potentials are obtained when the same charge is introduced into two conductors that differ only in shape. The ratio between the charge introduced into a conductor and the potential thus acquired is known as the capacitance of the conductor. The same charge can result in a higher or lower potential for different conductors; in other words, their capacitance depends on their material, size, and shape.

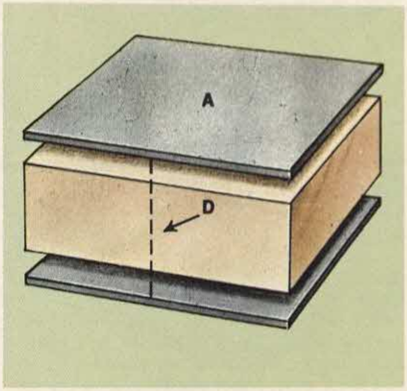
THE CAPACITANCE OF BODIES IN CLOSE PROXIMITY

An interesting phenomenon takes place when a charged sphere with a measured potential is placed close to another sphere with an opposite charge: the potential of the first sphere (and also that of the second) is lowered.

If the conductor consists of a flat plate, there is a large decrease of potential. In such a case, when a second flat conductor is brought close to the first plate, the effect is more pronounced than when two spherical conductors are placed close together; the decrease in potential is much greater.

An arrangement of two similar flat metal plates is used in a device which used to be called a condenser. Two flat metal plates in close proximity were thought to condense the electric charge that is introduced, producing a potential lower than that produced by one isolated plate. The name "condenser," however, is inappropriate; the charge is not condensed but is simply unable to create the electric field it would under other conditions. The name used today for such a device is "capacitor," because the device possesses a high capacitance and is constructed precisely for this purpose.

2



THE CAPACITANCE OF A CAPACITOR—A flat capacitor consists of two parallel metal plates close together. Its capacitance depends on the area of the two plates, their distance from each other, and the dielectric constant of the material placed between them. The larger the dielectric constant, the greater the capacitance. In fact, when other geometrical conditions are equal, a high dielectric constant lowers the value of the field and of the potential, thus increasing the capacitance. The capacitance is given in the formula:

$$C = \frac{D}{K\epsilon_0 A}$$

when A is the surface area of the plate, K the dielectric constant of the interposed material, and D the distance between the plates. If A is measured in square meters and D in meters, C will be expressed in farads.

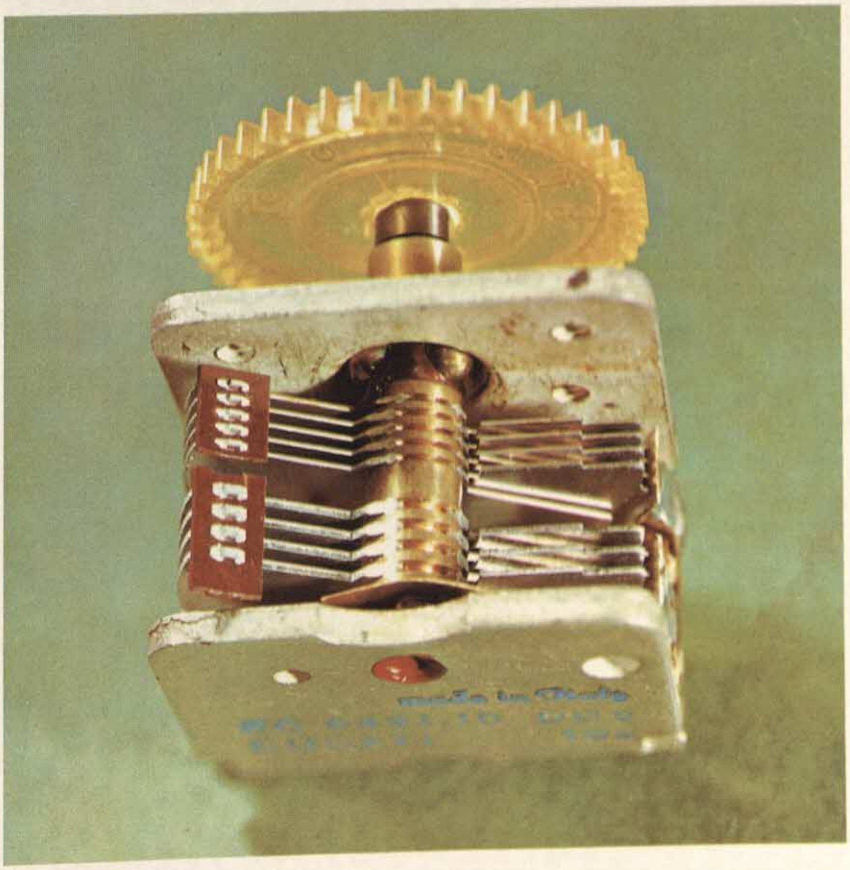
Many kinds of capacitors are used in electric circuits.

The unit of electric capacitance is called a farad, in honor of the English physicist Michael Faraday, a pioneer in the study of electrical phenomena. One farad has a potential of one volt when charged with one coulomb. This capacitance is so exceptionally high that it has never been used in any electric circuit. A capacitor with such a capacitance would be able to hold a charge containing all the electrons in a gram of hydrogen, attaining a potential of almost 100,000 volts.

An imaginary 1-farad capacitor would consist of two square plates at a distance of 1 mm (about .04 in.) from each other with a surface area of 110 km^2 (about 42 mi^2). In practice, much smaller capacitances are used, such as the microfarad (a millionth of a farad) and the picofarad or micro-microfarad (a millionth of a millionth of a farad).

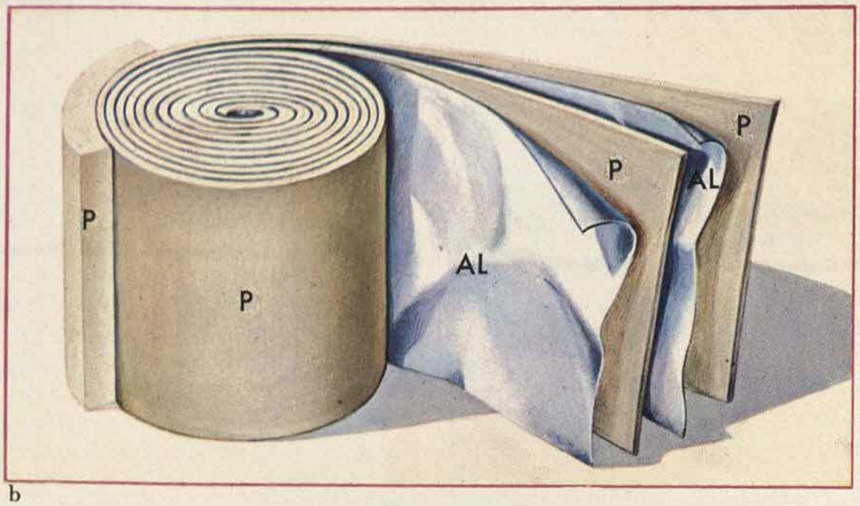
A CAPACITOR IN AIR—In radio circuits, variable capacitors are often used to tune the circuit that receives radio waves on different frequencies. These capacitors are made of plates that can be rotated to face each other over larger or smaller areas, thus producing a variation in capacitance.

3



4

a



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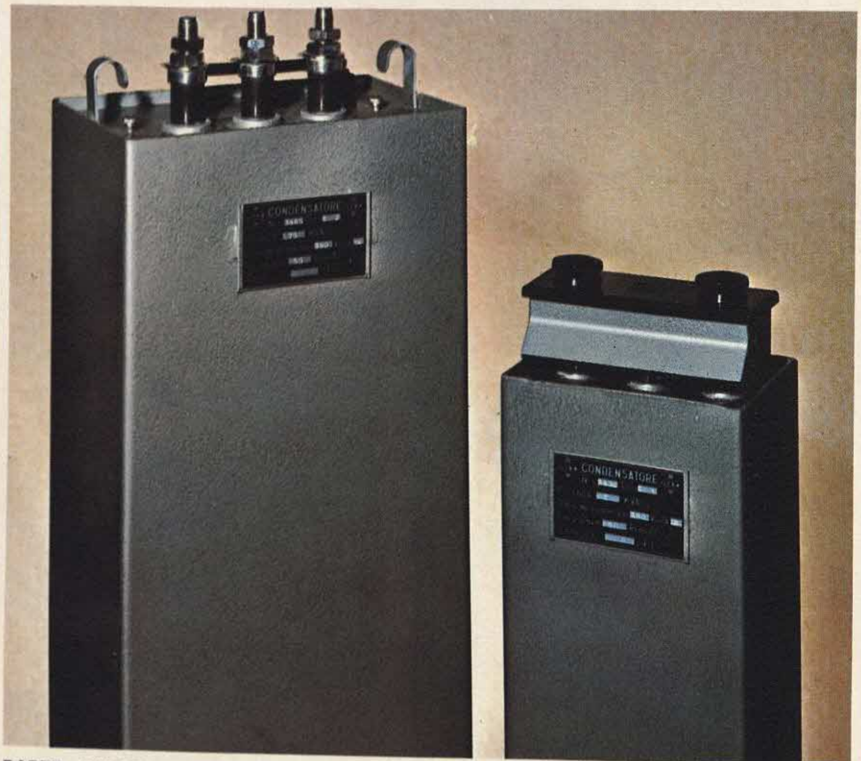


PAPER CAPACITORS—When high capacitances (those ranging from a picofarad to a microfarad) are required, the paper system (Illustration 4a) is used. Two thin aluminum strips, separated by two slightly thicker strips of paper to ensure there is no contact between the strips of aluminum, are rolled up. The capacitor thus formed is enclosed in a container saturated in an insulating material, such as polyester, epoxide, acrylic resins, or paraffin (Illustration 4b). Illustration 4c shows several types of capacitors with different capacitances and different maximum resistances to the amount of current with which they can be charged. Too high a current would produce a discharge that could perforate the dielectric and thus render the capacitor useless. Substances with a high dielectric constant are also good insulators and make it possible to produce high-resistance capacitors. The thickness of the dielectric is an important factor, and high-resistance capacitors are, therefore, larger than those with the same capacitance but a lower resistance. The increased thickness of the dielectric between the metal sheets increases the volume of the capacitor.

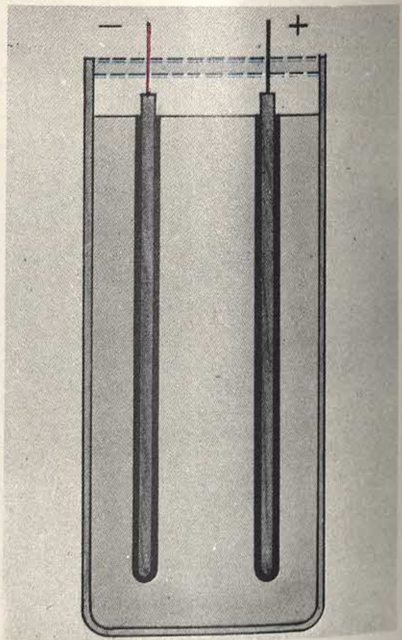
c

5

ELECTROLYTIC CAPACITORS—When a capacitor is used in a circuit in which the same (positive or negative) charge is applied to both its electrodes, two oxidized metal plates can be used as the electrodes. Aluminum (which has an oxide with a very high dielectric constant) is normally used, immersed in a liquid that causes the formation of a thin film of oxide over the surface of the metal. In such a capacitor (Illustration 5a), the liquid is one electrode and the metal is the second, while the oxide is the dielectric. The film of oxide is only a few thousandths of a millimeter in thickness and the two electrodes are thus very close and the dielectric constant very high. A 3-volt capacitor with a capacity of 10,000 microfarads may be no larger than a man's fist.

These high-capacitance electrolytic capacitors (Illustration 5b) are connected to the power supply in accordance with their polarity. Otherwise, a reverse current is obtained which results in the destruction of the oxide film and the consequent loss of function.

a



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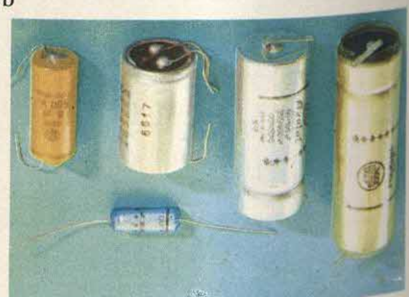

CONDUCTORS AND DIELECTRICS

free and captive electrons

The commonly used term *electric charge* is far from specific. It may refer to a charge that is produced on anything: to a scrap of paper charged by rubbing, to an atom that has gained or lost an electron, or even to a fast airplane that has become charged as a result of friction with the air through which it moves. An in-depth study of electric phenomena takes into consideration the behavior of individual electrons and of ions, which are atoms that have gained or lost an electron. Electrons and ions unite to form the neutral atoms that compose ordinary matter.

Matter can be divided conveniently into two large categories depending on the manner in which their electric charges behave. First are the conductors –bodies in which electric charges move fairly freely. Second are the insulators, or dielectrics–bodies in which charges are more or less immobilized. In the case of alternating currents, however, the dielectric characteristics vary according to the frequency of the alternating current. Some materials, for example, are poor conductors at low frequencies. In recent years the existence of matter that has properties midway between the two has been acknowledged. Such matter is known as semiconductors.

The microscopic structure of a conductor has been compared to a kind of sponge made up of immobile positive charges and mobile electrons that move from one part of the body to another. The positive charges consist of atoms that have been stripped of one or more electrons.

In dielectrics, all electrons are generally bound to the nucleus in such a way that the atom is complete and neutral. The electrons become detached only under exceptional circumstances. This fundamental distinction between conductors and dielectrics provides the basis for an understanding of the electrical phenomenon known as induction.

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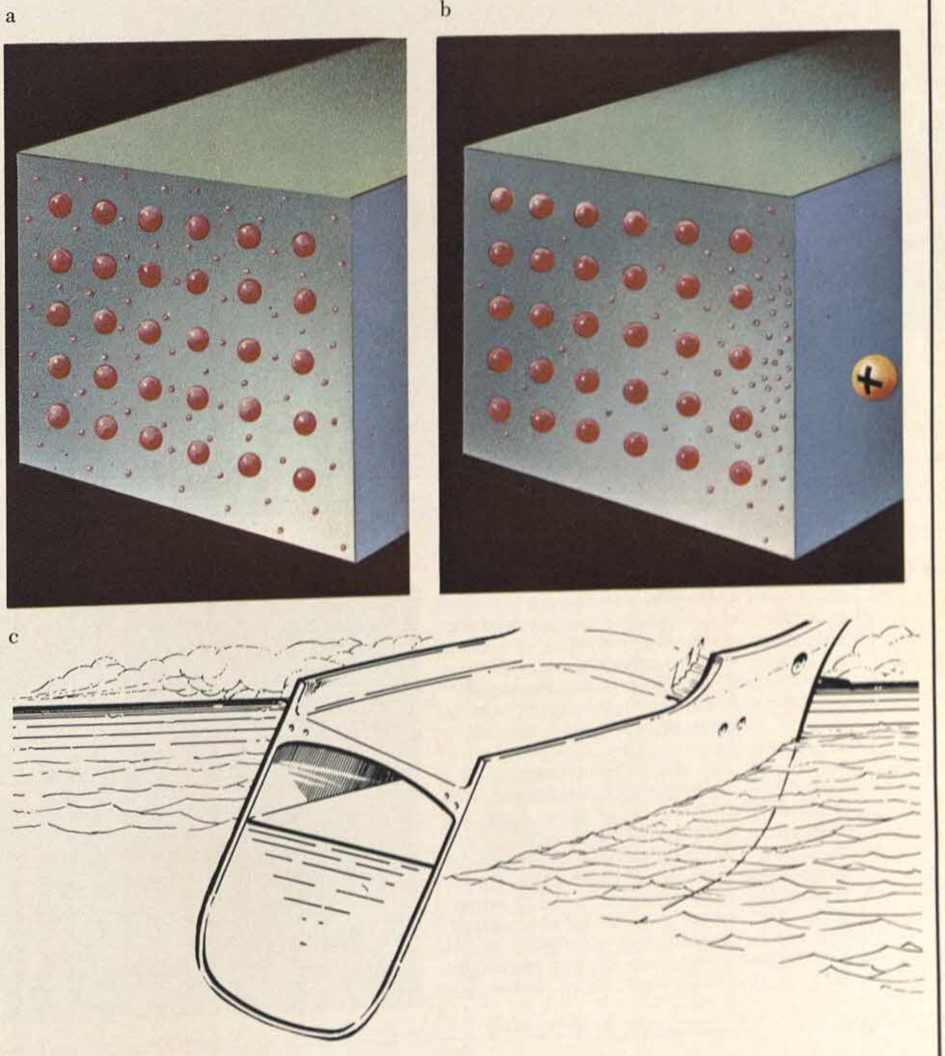
A CONDUCTOR BODY—Illustration 1a shows the internal structure of a conductor, which consists of atoms arranged regularly to form a kind of grid. Each atom has lost an electron, leaving the atoms positively charged. Free electrons are in neutral equilibrium; they do not reattach themselves to any ion and are fairly equally distributed among the positive ions. If they were to accumulate in a particular area of the body, an excess of negative charges would occur at that point; these charges would tend to move away from each other because of the repulsion forces that exist between like charges.

If a positive electric charge were brought close to this body (Illustration 1b), all the electrons, instead of remaining evenly distributed, would be attracted to the positive charge. The opposite side of the body, left without electrons, would appear to be positively charged.

Although it is not always possible to find a mechanical equivalent for electric phenomena, a fairly accurate mechanical analogy illustrates the composition of a conductor. Imagine that a piece of conductor material, such as a metal, resembles a loaded oil tanker (Illustration 1c). When the ship rolls, the liquid moves toward the low side of the ship. As the ship returns to an even keel and rolls to the other side, the liquid follows the direction of roll. As the liquid is free to move within the hull of a tanker, electrons are similarly free to move inside a conductor when they are attracted by an exterior electric field.



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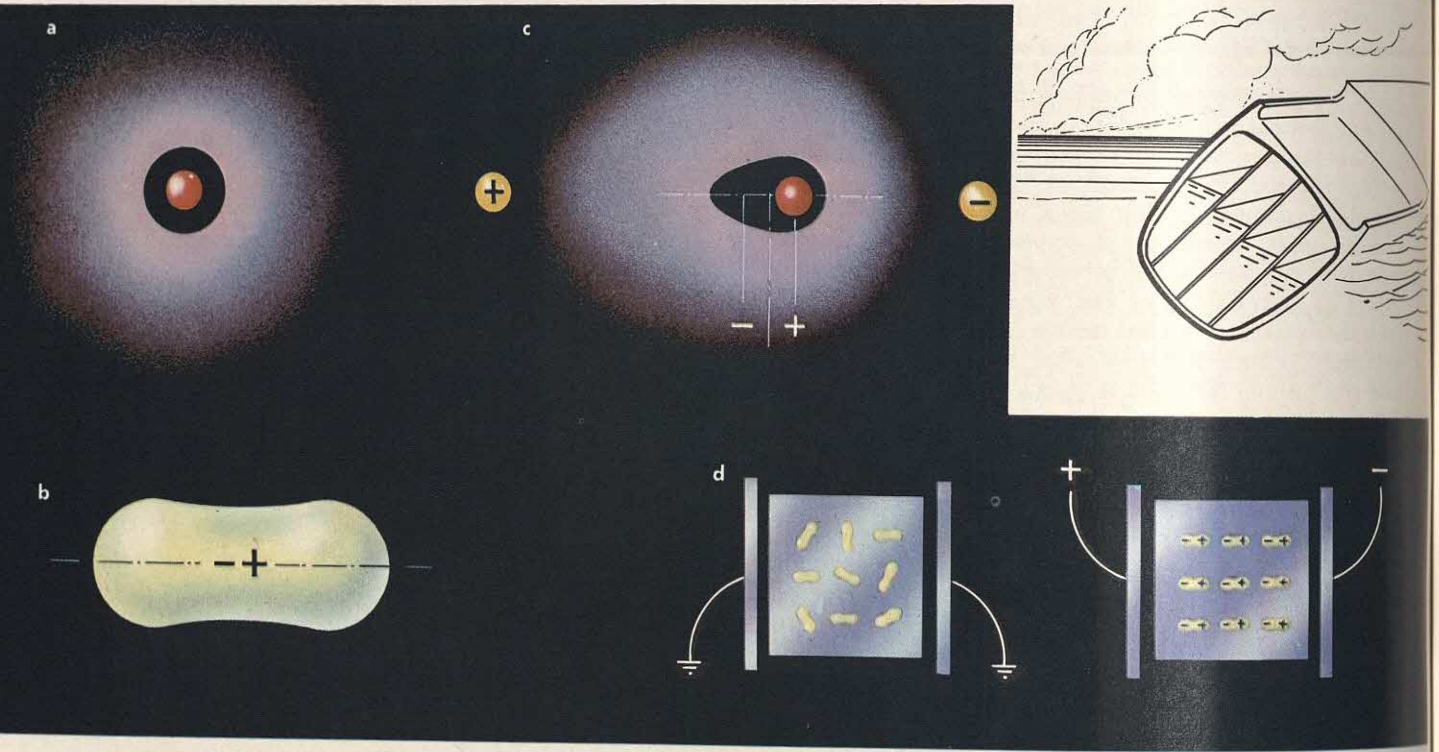

DIELECTRICS—Substances whose atoms and molecules do not easily release their electrons are known as dielectrics. In this respect they differ from conductors, which are usually metals in which electrons move fairly freely. An important distinction exists with regard to the arrangement of the positive and negative charges of the atoms and molecules in dielectrics. An atom such as that shown in Illustration 2a has a positively charged nucleus, while the negative charges—the electrons—rotate around the nucleus, forming an electronic cloud, shown here as a violet halo. The electrons are normally distributed symmetrically around the nucleus, causing the center of gravity of the positive charges to coincide with that of the negative charges. Atoms of this kind, and molecules having the same

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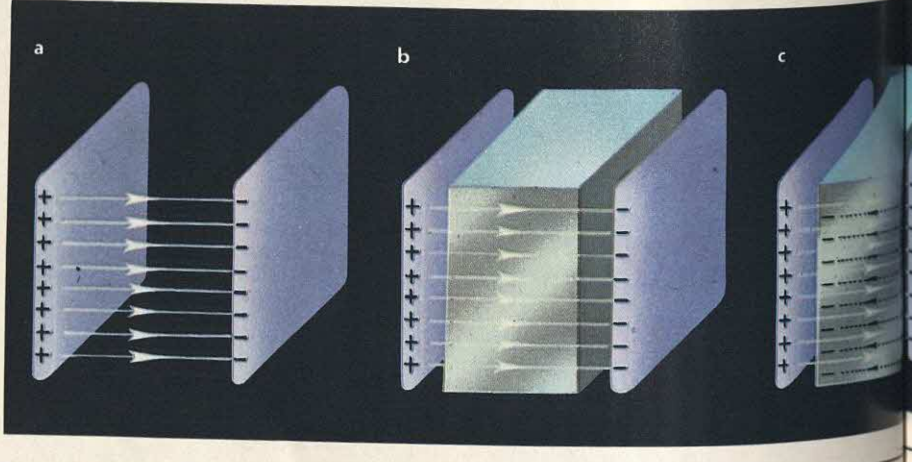
INDUCED CHARGES—In studying electric phenomena, it is usually necessary to create an electric field. An electric charge introduced into a certain area of space will attract opposite charges and repel like charges. To obtain a uniform electric field in which the forces at any point in the space are equal and parallel, two flat metal plates are placed parallel to, and at a set distance from, each other (Illustration 3a). The plates are connected to a source of electricity that will keep one positively charged and the other negatively charged. In the experiments shown here, the plates can be connected to the opposite poles of a battery and then disconnected. Further experiments may require the plates to be permanently attached to a generator of current. The arrows leading from one plate to the other represent the force lines of the electric field. In this experiment, if an undisturbed



properties, are known as nonpolar atoms or molecules.

Other molecules exist in which the centers of gravity of the positive and negative charges do not coincide. Under normal conditions, such molecules, even if they contain an equal number of positive and negative charges, behave as if they were electric dipoles—bodies made up of two opposite charges at a certain distance from each other (Illustration 2b).

If a nonpolar molecule or atom is placed in an electric field, such as between two opposite electric charges, the positive charges are attracted toward the external negative charge, while the negative charges are attracted in the opposite direction, toward the external positive charge. The nonpolar molecule has become polar, but it will become nonpolar again when the external field is removed. Illustration 2c shows how the electronic cloud becomes distorted when the atom is placed in an electric field.

A polar molecule (or a polarized nonpolar one) placed in an electric field will orient itself, turning until the center of gravity of the negative charges is closer to the positive charges that are generating the field. However, as Illustration 2d shows, no molecule changes its location, and the internal charges make only a negligible movement.

Using the oil tanker analogy, this time with its liquid cargo divided into a number of adjacent compartments (Illustration 2e), when the ship rolls, the liquid in each compartment shifts toward the side of the roll. There is still a slight general movement of the liquid toward one side of the vessel, but the movement is not so great as it would be if the liquid were contained in a single large compartment. In this analogy, as in that for conductors, the liquid corresponds to the electrons in the material.

SEPARATION OF CHARGES—Here, as in Illustration 3, a conductor is introduced between two electrically charged plates and becomes charged. This time the conductor consists of two metal spheres, initially in contact but easily separable. The spheres have insulated handles. One of the spheres becomes positively charged and the other negatively charged. If the spheres are separated from each other, they will remain charged, one positively, the other negatively. They are said to have been permanently charged by induction.

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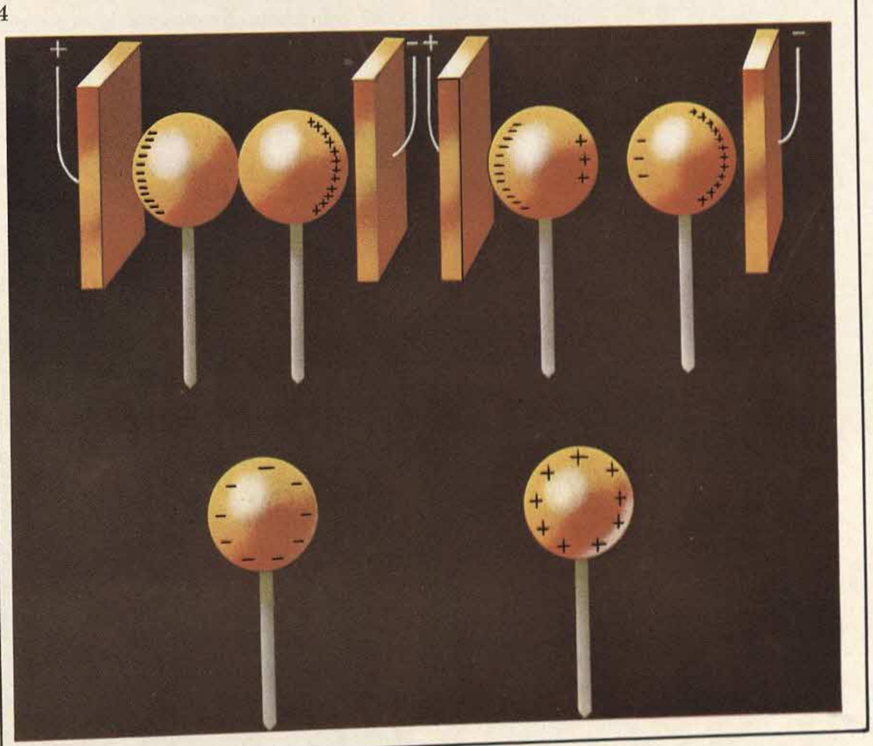

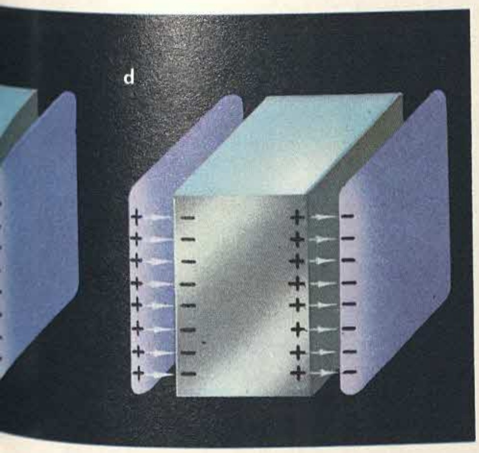

vacuum or a rarefied gas exists between the plates, the field will not undergo any change and will remain as shown in the illustration.

If a rectangular slab of a conductor material, such as a piece of copper, is introduced between the two plates without touching them, for a very short time—about a hundred millionth of a second—the free electrons in the slab will be affected by the force of attraction or repulsion of the electric field between the two plates. As might be expected, the free electrons inside the conductor body become concentrated on the side of the slab facing the positive plate (Illustration 3c). Consequently, no negative charges will remain on the opposite side of the slab, which will be positively charged. The charges on the two opposite faces of the slab will, in their turn, produce an electric field like the one between the two plates, but acting in the opposite direction because their poles are oppositely charged to those of the plates facing them.

Inside the slab, the electric field created by the two charged surfaces of the conductor slab will cancel the effect of the field between the charges on the plates connected to the opposite poles of the battery.

The presence of the conductor has completely cancelled the initial electric field except in the narrow space between each plate and the side of the conductor slab facing it (Illustration 3d). The effect of introducing a conductor body into an electric field has produced a movement and separation of charges as well as a cancellation of the field in the area occupied by the body. This phenomenon, known as induction, lasts as long as the conductor remains in the inductor field. When the conductor is removed, it becomes neutral again because its electrons redistribute.

THE DIELECTRIC CONSTANT

a number that defines electric behavior

Important as they are, electric conductors would be of little use were it not for their opposites, insulators, whose value lies in the fact that they are poor conductors of electricity. Insulators are sometimes called dielectrics, and their behavior is expressed in terms of a number: the dielectric constant.

An electric charge in a vacuum generates an electric field capable of exerting forces on any other charges placed nearby. These forces, in fact, extend infinitely but they become virtually imperceptible within a short distance. When a conductor is placed in a space where electric forces are being generated by charges, the field has the effect of displacing the charges in the conductor. The charges in the conductor become arranged on its surface so that the net field inside the conductor is zero. When a dielectric is placed in an identical space, the result is quite different, as shown in Illustration 1.

In a dielectric the electric charges remain close to the individual atoms or molecules and are thus subject to polarization. When polarized, the charges in the molecules of a substance move in the vicinity of the molecules according to the law of the attraction of opposites, and the molecules create a dipole in which there is a separation between the centers of positive and negative charges. This means that certain molecules become elongated or change their position until their charges are oriented in the direction of the field.

SUSCEPTIBILITY AND THE DIELECTRIC CONSTANT

Illustration 1 shows a slab of dielectric material placed between a pair of charged conductor plates. It is evident that the strength of the field E_1 inside the dielectric must be less than that which would exist if the dielectric were not there, because the charges that have been brought to the surface of the dielectric have partially neutralized those of the plates creating the original field. The strength of the effective charge producing the field inside the dielectric is equal

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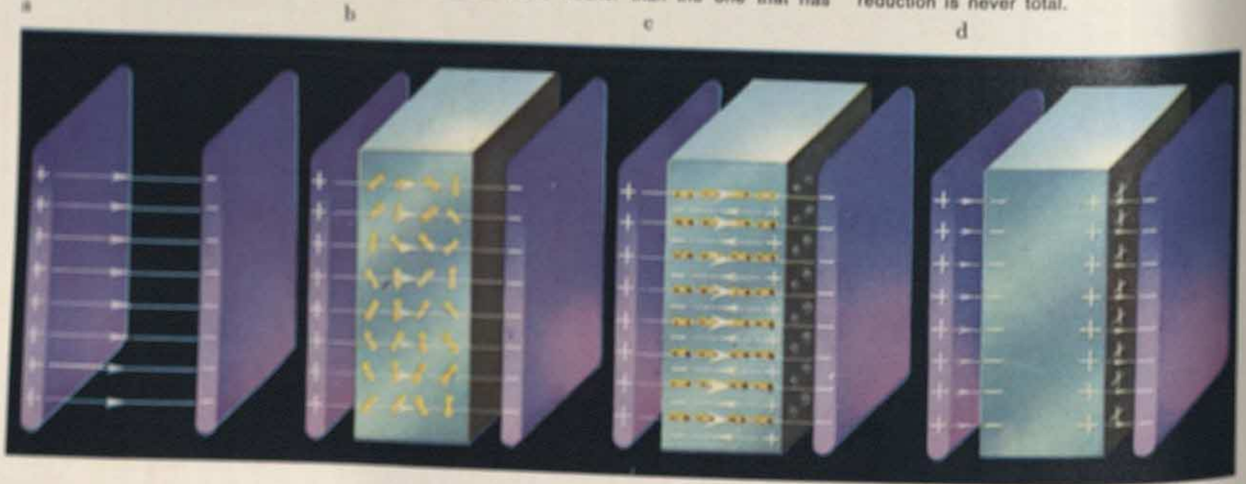
A DIELECTRIC IN AN ELECTRIC FIELD—Illustration 1 shows what happens in a dielectric when it is placed in an electric field. The field is generated by two metal plates connected to a battery. One of the plates becomes positive and the other negative, and an electric field is set up between them. Then the molecules, which contain positive or negative charges, turn (offering greater or less resistance, depending on how strongly they are attached to each other inside the substance) to line up according to the force lines of the electric field. This is the phenomenon of orientation. The molecules have been shown as ovals in which the centers of gravity of the electric charges have been separated, the positive charges to the right, the negative ones to the left. Next, each molecule faces the one next to it, presenting its oppositely charged side, so that the positively charged side of one molecule faces the negatively charged side of the next. In this way, provided the field is homogeneous, the average effect of the electric charges created by the polarization of the molecules inside the dielectric is nil. On the external faces, however, there will be charges opposite to those on the plates that produce the field into which the dielectric has been placed. In Illustration 1a, an electric field is set up by placing two metal plates face to face. If a vacuum exists between the plates, the field will be established without interference. Next, a dielectric is placed quickly between the two plates. For a brief instant, nothing at all happens. The force lines of the field remain unimpeded (Illustration 1b). Very soon the electric dipoles of the molecules of the dielectric become oriented and cancel each other internally. On the surfaces, however, two layers of charges, oppositely charged to those on the plates they are facing, are formed, as shown in Illustration 1c. These two layers of induced charges produce an electric field, weaker than the one that has set it up, but opposite to it and neutralizing it to some extent inside the dielectric slab. This is shown by arrows pointing in the opposite direction to those of the original field.

Illustration 1d shows the final result: The field produced by the charges induced on the surfaces of the dielectric cancels some of the force lines of the original field inside the slab. The electric field inside the dielectric is therefore weaker. In the space between the plates and the dielectric, the field is unaltered.

The electric field inside the dielectric is reduced in strength by the orientation of the dipoles present in the polarized molecules. If a metal slab were introduced between the two plates, the effect would be to cancel completely the electric field inside the metal, provided the metal was a good conductor of electricity. As for the dielectric, the amount of reduction of the field inside it depends on the substance that has been introduced, but the reduction is never total.



to $d - d_i$, where d is the strength of the charge present per unit area of the faces of the conductor plates, and d_i the charge per unit area on the surfaces of the dielectric slab.

The electric field, E, in the dielectric is equal to the difference between the field produced by the external charges and the field on the surfaces of the dielectric. Because an electric field is directly proportional to the strength of the charge, it can be written

$$E = \frac{1}{\epsilon_o}(d - d_i) = \frac{1}{\epsilon_o} d - \frac{1}{\epsilon_o} d_i.$$

ϵ_o represents the proportion between the electric field and the strength of the charge that produces it. The strength of the charge induced on the faces of the dielectric depends both on the strength of the field E and on the nature of the dielectric. This can be expressed by the formula, $\delta_i = \chi\epsilon_o E$, meaning that the strength of the charge is proportional to the field E that produces it. χ is the electric susceptibility of the dielectric and depends on the material of which it is made; the higher its value, the smaller the field needed to produce a high induced charge. The above relationship between field and strength of charge can thus be expressed purely in terms of E, ϵ_o and χ. The first is a known quantity, the field; the second is a known constant, as is the third, which depends on the material chosen.

Therefore,

$$E = \frac{\delta}{\epsilon_o} - \chi E,$$

and so

$$E = \frac{\delta}{(1+\chi)\epsilon_o}.$$

The expression $(1 + \chi)$ is normally indicated by κ; thus,

$$E = \frac{\delta}{\kappa\epsilon_o}.$$

κ is called the relative dielectric constant (relative to a vacuum) of the dielectric, which varies from one dielectric to another.

The word *constant* in *dielectric constant* is imprecise. This value is, in fact, a function of the temperature and strength of the field. Further, its value is determined in the case of a constant electric field. If the field is variable or alternating, the value of κ varies. In solids such as glass, when the temperature and intensity of the electric field are held fixed, the dielectric constant *is* constant whatever the direction of the electric field inside the glass. In a crystal of complex structure, however, its value will depend on the direction in which the slab was cut before being inserted between the plates to induce the field. In general, nine numbers are needed to define the dielectric constant.

The following table gives the value of the dielectric constant for some commonly used substances:

Material	*Dielectric Constant*
vacuum	1
ice (−5° C)	2.9
glass	5–10
mica	3–6
rubber	2.5–3.5
wood	26–8
ethyl alcohol (0° C)	28.4
ethyl alcohol (−120° C)	54.6
glycerine (5° C)	56
water	81
air (1 atmosphere)	1.0059
TiO_2	170 (if the electric field is parallel to the main axis of the crystal)
TiO_2	86 (if the electric field is perpendicular to the main axis of the crystal)

To summarize: If a dielectric is placed between two plates, oppositely charged, the electric field inside the dielectric depends on the nature of the dielectric, and more exactly on its dielectric constant; the greater the dielectric constant, the smaller the field.

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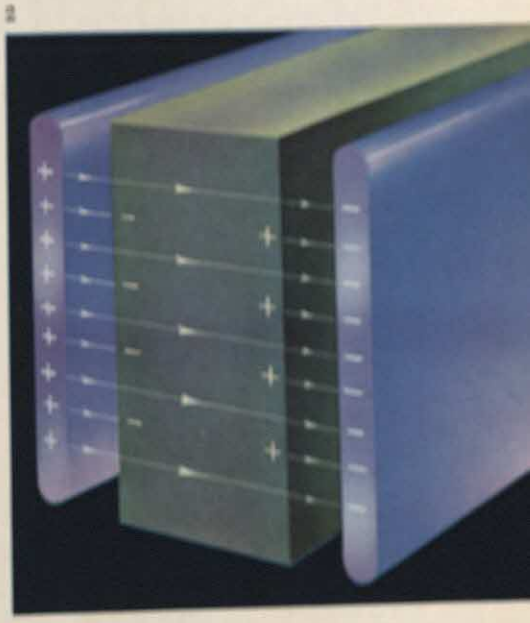

SUSCEPTIBILITY AND THE DIELECTRIC CONSTANT—This illustration shows the distribution of the charges and direction of the field on the surfaces of a dielectric placed in an electric field. It is similar to illustration 1d, but emphasizes the presence of charges on the surfaces of the plates and dielectric. It shows, in particular, that the number of charges per unit of surface is less on the dielectric than it is on the plates. The density of the charges on the surfaces of the plates producing the field, the induced density on the dielectric surface, the applied electric field, and the field induced in the dielectric are quantities that can be used to define the electric susceptibility and the dielectric constant of the dielectric into which the phenomenon of induction has been introduced.

ELECTRIC CURRENT | electrons in movement

Neither an elaborate laboratory nor sophisticated equipment is necessary to demonstrate certain electrical phenomena, in particular, electrostatics. Hair is attracted to a comb during combing, the sides of a plastic bag stick together stubbornly, dust clings obstinately to a phonograph record when the disk is rubbed with a cloth—each is a manifestation of electrostatics, which is the phenomenon of electrically charged bodies at rest. Most electrical phenomena, particularly charged bodies in motion, require delicate laboratory equipment. These phenomena originate at the atomic levels in which particles are charged with elec-

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EXAMPLES OF ELECTRIC CURRENT—An electric current exists as soon as a charge is in motion. This movement can occur in matter—a solid, a liquid, a gas—or in a vacuum. Here are some examples:

Illustration 1a shows how the movement of a charge occurs when some of the electrons that are free to move in a conductor move from one end of the conductor to the other, or at least move in an orderly manner in the conductor.

If the ends of two wires connected to the poles of a battery are immersed in a solution of salt water, the ions in the water, in which the molecules of salt have become dissociated, are set in motion (Illustration 1b). The ions will move toward the ends of the wires, with the positive ions moving toward the negatively charged wire and the negative ions moving toward the positively charged wire. This double movement of charges toward opposite poles is an electric current.

An electric charge such as a flash of lightning or a spark (Illustration 1c) is a phenomenon of the passage of current through a gas such as air. The molecules of air are broken up into positive ions and electrons, which have a negative charge. Both ions and electrons move, attracted by the opposite poles between which the discharge takes place—the two electrodes in a high-voltage device, or, in the case of lightning, two clouds or a cloud and the ground. This movement of charges constitutes an electric current.

Illustration 1d shows a special case of electric current, that of the beam of particles that emerge from an atomic particle accelerator. The charged particles are made to move parallel to each other in a vacuum tube.

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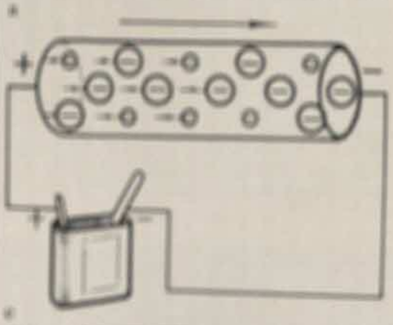

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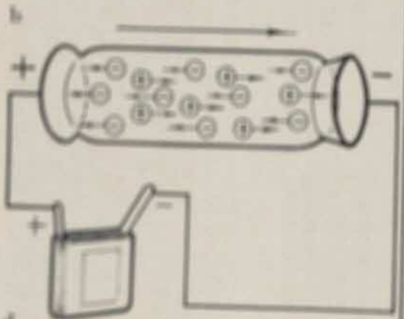

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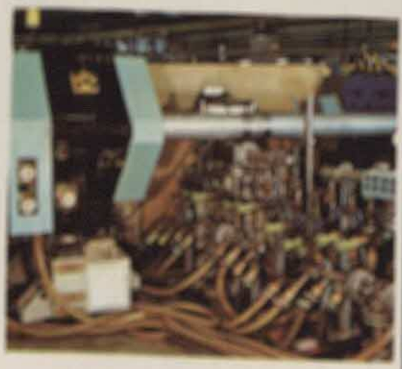

MEASUREMENT OF A CURRENT—Illustration 2 represents an electric conductor (as if it were possible to see inside a piece of copper wire), showing the electric charges (the electrons) as small spheres moving from right to left. Two imaginary disks have been drawn across the wire. The magnitude of the electric current is the amount of electric charge that crosses from one disk to the other in a unit of time, a phenomenon expressed as follows:

$$I = \frac{q}{t},$$

where I is the current, q is the charge, and t is the time in which that amount of charge has passed between the disks.

In defining current, it is understood by convention that the flow is made up of positive charges. When dealing with a conductor made of metal or other material through which charges move, an electric current can be represented by an arrow parallel to the conductor. Because the current in a conductor is caused by the movement of negative electric charges, the electrons, the arrow will point in the direction opposite to that of the electron movement. In a beam of positive particles emitted by an accelerator, the electric current moves in the same direction as the particles. In an electric discharge or an electrolytic solution such as salt water, the charges that move are positive and negative, but by convention the current runs in the direction of the positive charges.

The formula $I = q/t$ permits the calculation of a unit of measurement for the current. If the coulomb is used as the unit of charge and the second is used as the unit of time, the unit of current will be the coulomb/second, or C/sec, also known as an ampere. An ampere is a very large unit. For example, one ampere is the approximate current that runs through the conductor feeding the compressor motor of a large home refrigerator. A thousandth of an ampere is a milliampere; a millionth of an ampere, a microampere; and a billionth of an ampere, a nanoampere.

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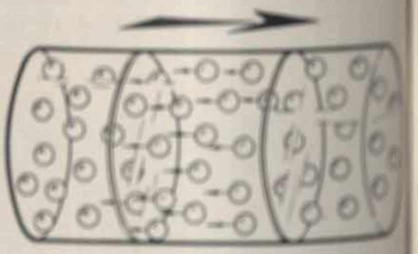

tricity and interact dynamically according to complex laws.

In electrical phenomena a particular kind of energy is always in play. Machines can be used to transform electrical energy into mechanical or thermal energy, or, conversely, to transform mechanical or thermal energy into electrical energy. This capability of transformation of energy and the ease with which electrical energy can be conducted along wires, from a high-voltage source to the wiring of electrical outlets in the home, have enabled man to utilize electrical energy that is produced in different ways.

The transmission of energy over long distances is governed by laws that regulate current—the movement of electrical charges through matter and space. A moving charge is an electric current. The trajectory of the moving charge is the path of the current.

THE VELOCITY OF ELECTRONS INSIDE A CONDUCTOR

The speed at which electrons move inside a conductor can be calculated. For example, the velocity of electrons in a copper conductor 1 cm (about 0.33 in.) in diameter transporting a current of 200 amperes involves knowing that 200 coulombs of charge pass through the cross-section of the conductor every second, knowing how many electrons make up a charge of 1 coulomb, and knowing how many free electrons are contained in a cubic centimeter of copper. Electrons move along the wire at a velocity of 2/10 of a millimeter (about 0.0008 in.) per second, or about 3 ft an hour—a rather modest speed. The ease with which current can pass varies enormously from one substance to another. Metals are the most effective conductors.

Many persons believe current flows at lightning speed. On the contrary, it flows slowly. What is propagated at an astonishing velocity is the initiation of the motion of the electrons. When electrons are set in motion by the application of a suitable electric field, all electrons are not set off simultaneously all along a wire, but in very rapid succession. This phenomenon is similar to a line of automobiles starting up at an intersection when the traffic light changes to green; the cars do not all move together, but one after another.

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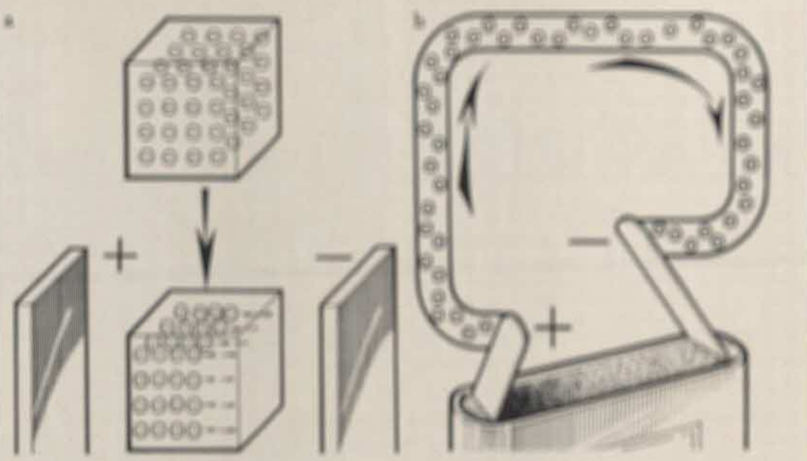

PRODUCING A CURRENT—If a conductor is moved into an electric field, the mobile charges contained in the conductor will be set in motion in a very brief space of time in the direction of the two electrodes that form the field (illustration 3a). The electric field modifies the internal equilibrium of the conductor, and the free charges move to restore the equilibrium. As soon as the charges have been displaced, the current stops, so in order to obtain a continuous flow of charges (a continuous and constant current), a device is required that will keep the internal equilibrium unbalanced by collecting the charges that arrive at one end of the conductor and circulating them back to the opposite end. Such a device may be a battery (illustration 3b) or a generator, or other similar device.

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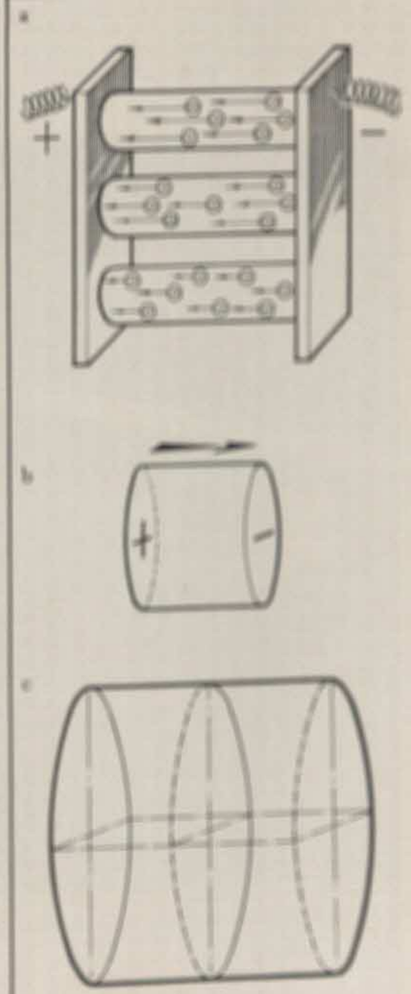

ELECTRICAL RESISTANCE—If small cylinders of different conductors are placed between two electrodes connected to a battery, the two ends of the conductors will be kept at a constant difference of potential (illustration 4a). The charges between the two electrodes, both those in the conductors and those in the air, are stimulated to move from one end to the other. Scientists speak of the potential of a field of gravity, and also of the potential of an electric field. The height from which a body may fall in a field of gravity is analogous to the characteristic of an electric field that controls the ability of the charge to release more or less energy in moving from one point of the field to another, between which there is a known difference in potential. This applies when the charge is in a vacuum. If the charge is in matter, the electric field itself and the difference in potential will cause a greater or lesser flow of charges, depending on the substance of which the material is made. All materials offer a certain resistance to the passage of electric charges. If the resistance is high, the flow of charges is low, and vice versa. A material that has a strong resistance is an insulator, or poor conductor. Most metals are good conductors; certain metals, such as copper and silver, are excellent conductors.

The resistance of a material is the opposition it offers to the passage of electric current. The resistance of a given piece of material of known length, cross-sectional area, and temperature (illustration 4b) is defined as the ratio of the potential difference between the two ends of the material and the current flowing. If the potential difference is measured in volts and the current in amperes, the resistance is expressed in units known as ohms, after G. S. Ohm, a German physicist who studied the phenomenon of electrical resistance and defined its laws.

Illustration 4c shows a conductor of another size, but of the same material as the conductor in 4b. In general, the resistance of the larger conductor will be different. There is, however, a quantity called resistivity (the unit of measure of which is the ohm-centimeter), which is characteristic of the material and does not depend on size or shape.

MEASUREMENT OF SMALL CURRENTS

simple devices for obtaining great accuracy

Galvanometers—instruments used to measure small electric currents—have been used in the discovery of many important scientific phenomena in the past century. They are still widely used in scientific work. Today, they have been so refined that some can measure currents of less than a ten-billionth of an ampere. Not all galvanometers are as sensitive as this, but regardless of their sensitivity, they are delicate instruments that must be operated with great care. Because the galvanometer is a complicated and delicate instrument that may yield measurement errors due to the many difficulties inherent in its construction, the study of its use can serve as a guide to the possible sources of error in other scientific instruments.

In its common form, the galvanometer consists of a light coil of wire suspended between the poles of a permanent magnet by means of a copper or gold ribbon a few thousandths of an inch wide and less than a thousandth thick. A mirror, mounted on the coil, serves as an optical pointer by reflecting a light beam onto a fixed scale. When current is conducted to the coil, the reaction with the radial magnetic field causes the coil to rotate.

SETTING UP A GALVANOMETER—A galvanometer must be set up in a perfectly vertical position because the moving part of a galvanometer (usually a wire coil) must rotate in the space between the poles of the permanent magnet and the cylindrical block of iron used to create a magnetic field around the coil parallel to it. Therefore, only a perfectly vertical suspension of the coil can ensure that it will rotate freely and touch neither the poles nor the cylindrical block.

The first step in setting up the galvanometer is called plumbing the instrument (or "centering the bubble" because many galvanometers are equipped with bubble tubes to center on the vertical more easily). The first stage of plumbing the instrument consists of adjusting the leveling screws of the instrument until the coil can rotate freely.

After the screws have been adjusted, the instrument should be firmly based so that the indicating system will not oscillate because of an unstable galvanometer mounting.

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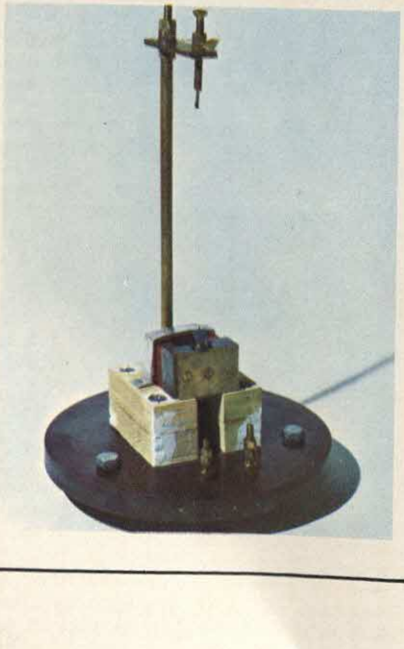

THE LIGHTING SYSTEM—The lighting system of a galvanometer consists of a stand that holds both a graduated scale made of ground glass and a light for the scale. The light and the scale must be placed exactly 1 m (3.28 ft) away from the small mirror of the galvanometer and in the position shown in this illustration. The exactness of the distance is important because the distance determines the calibration of the instrument.

The final adjustments to the lighting system should be carried out in the dark, or at least in dim light. The galvanometer light is set up so that the beam of light will fall onto the small mirror attached to the coil. The light, the scale, and the mirror must be arranged so that the image of the filament of the lamp will be at the center of the scale after having been reflected by the mirror under zero current conditions.

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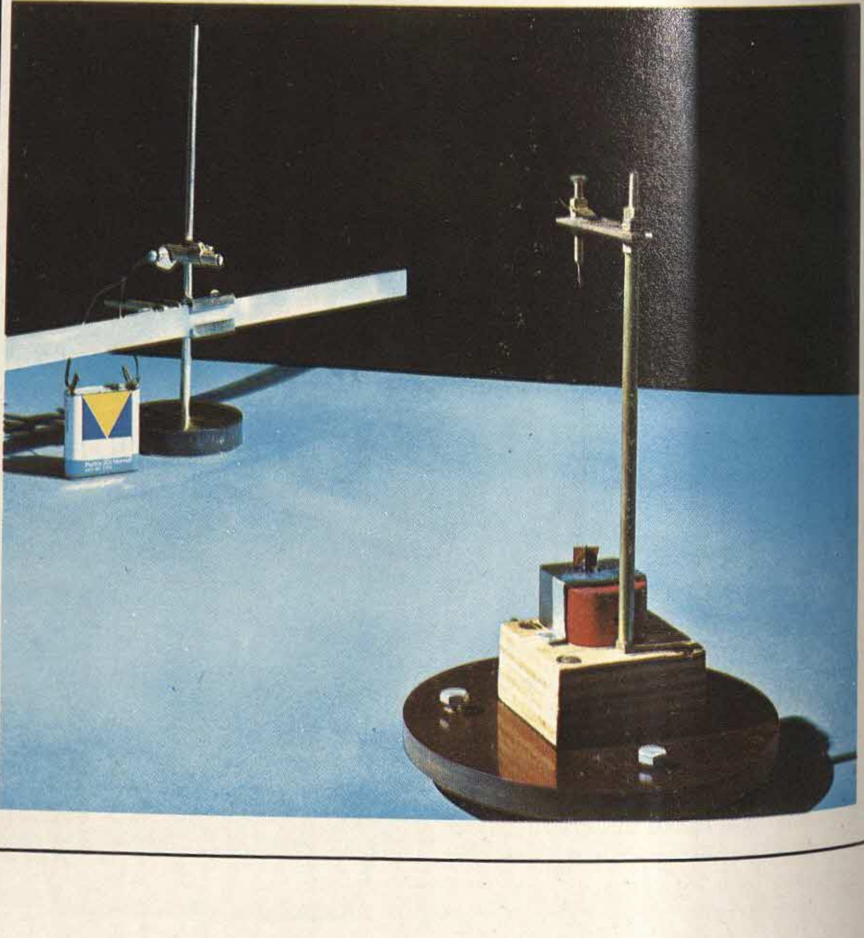

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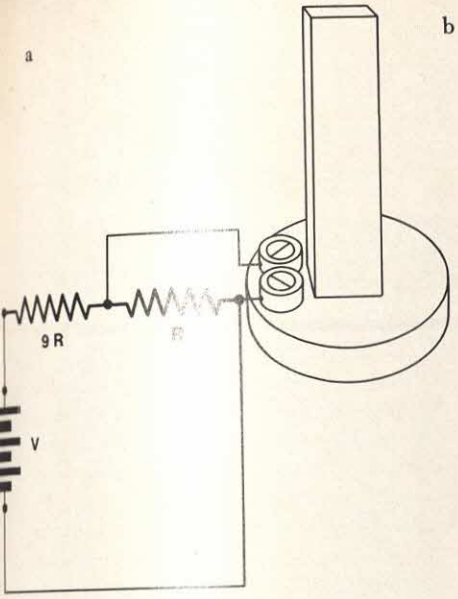

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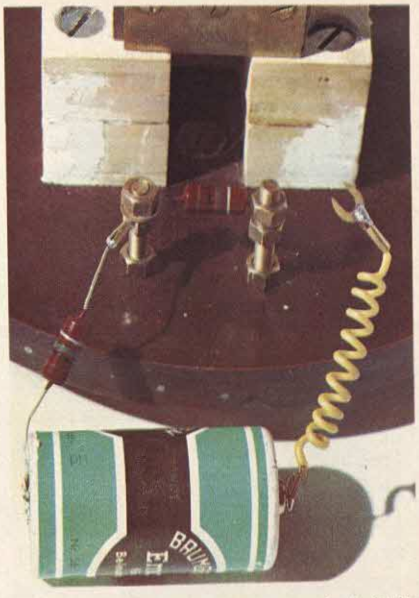


GENERATING VERY LOW VOLTAGES—In order to determine such galvanometer characteristics as internal resistance, scale factor, and linearity of the scale, sources capable of supplying direct current of very low voltage are necessary. Such a source may be built by connecting in series a single-cell battery and two resistors, one with a high value and one with a low, as shown in Illustration 3a. In this case the resistance on the left is nine times that on the right. Therefore, the voltage obtained from the terminals of the low value resistor will be one tenth the voltage of the battery (1.5 V) or approximately 0.15 V. Since the galvanometer being calibrated is sensitive to voltages on the order of one ten-thousandth of a volt or less, resistances that vary more widely between themselves must be used to obtain a much lower voltage.

Illustration 3b shows two resistors connected according to the diagram in Illustration 3a. One resistor has a resistance of one megohm (1×10^6 ohms); the second has a resistance of only 100 ohms. The free ends of these two resistors have been soldered to battery terminals and two conductors have been soldered to the ends of the 100-ohm resistor. The voltage obtained from the terminals of the 100-ohm resistor will be

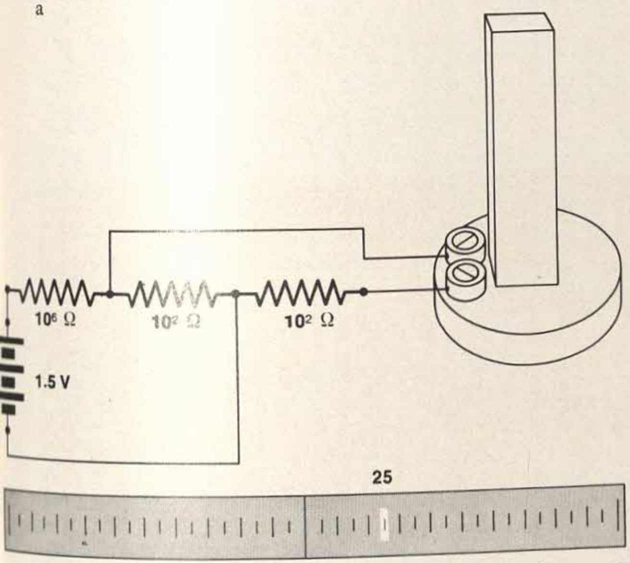
$$\frac{100}{1{,}000{,}000 + 100}$$

times the voltage of the battery, or approximately 0.00015 V.

Obviously, the accuracy of the value obtained for the voltage depends to a great extent on the accuracy to which the values for the resistances are known. If a resistor of low accuracy—for example, one whose value is specified as ±10 percent—is used, its exact value should be measured. Also, a new battery should be used, as the voltage of an old battery may fluctuate.

4

a



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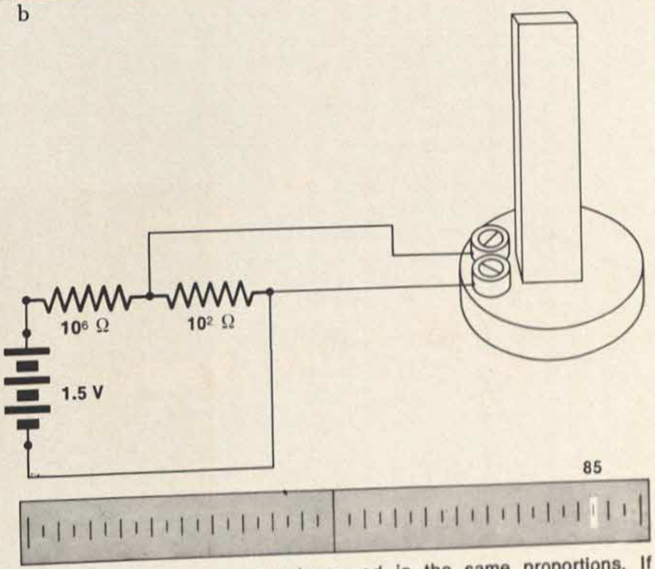

SENSITIVITY AND INTERNAL RESISTANCE OF THE GALVANOMETER—Before the sensitivity and internal resistance of a galvanometer can be measured, a voltage commensurate with the measuring abilities of the galvanometer must be established. Using the circuit shown in Illustration 3, connect one end of the circuit to one terminal of the galvanometer. Then, after the room has been darkened and the projector switched on, the two remaining terminals of the circuit are connected. There are three possible responses of the galvanometer: (1) the pointer of the galvanometer (which is the image of the lamp filament reflected onto the scale) will deflect very rapidly toward one end of the scale; (2) the pointer will remain perfectly still, or; (3) the pointer will move a short distance on the scale. Rapid deflection of the pointer is an indication that the voltages being generated are too high for the galvanometer and must be reduced. The same procedure used in Illustration 3 can be used again to decrease the voltages by powers of ten—or any other convenient factor—until the galvanometer responds by a slow deflection on the scale. If the galvanometer remains still, the voltages being generated are too small to be detected by it and must be increased by the procedure shown in Illustration 3. If the indicator moves slowly, the voltages being generated are of the right order, and the internal resistance and sensitivity of the galvanometer can be measured.

The following procedure is used to determine the internal resistance of the galvanometer. The source of the small voltage is connected directly to the terminals of the galvanometer, and the number of divisions that the pointer is deflected is counted. The same source is then connected to the terminal of the galvanometer, but with the addition of a resistor of known value (for example, 100 ohms) between one terminal of the source and the terminal of the galvanometer. The deflection of the galvanometer pointer will diminish. If the first deflection was 85 divisions and the second 25, the current flowing through the galvanometer has been reduced by a ratio of 25/85. Therefore, the total resistance of the galvanometer and the circuit must also have been increased in the same proportions. If the internal resistance of the galvanometer is x ohms, then

$$\frac{x}{x + 100} = \frac{25}{85}.$$

In this example, the internal resistance is 41.7 ohms.

Once the internal resistance has been measured, the sensitivity of the instrument can be easily calculated. Using the values shown in the paragraph above, and those described in Illustration 3, the current being measured is 0.00015/41.7 amperes (3.6 microamperes or 10^{-6} amperes), in accordance with Ohm's law. Thus, a current whose value is 3.6 microamperes causes a deflection of 85 units on the scale of the galvanometer. It follows that one unit of the scale will measure 3.6/85 microamperes (or 0.0424 microamperes), which is equivalent to 42.4 nanoamperes (10^{-9} amperes) per unit. The galvanometer, therefore, is sensitive to a current as small as approximately 40 billionths of an ampere.

THE LAWS OF ELECTRIC CURRENT

energy transmitted by wire

Electricity is now so familiar that only its absence can demonstrate its importance and usefulness. Anyone who has been caught in a house whose electric current has suddenly been cut off soon learns how closely the conveniences associated with modern life are tied to electricity. This article is concerned with the nature and some of the properties of electric currents from both a theoretical and applied standpoint.

DIRECT CURRENT

From the study of static electricity, which is concerned with phenomena stemming from the attraction and repulsion of stationary electric charges, certain facts are known. One such fact is that an electric charge interacts with other electrical charges in accordance with Coulomb's law. This law, first expressed by the French physicist Charles Augustin de Coulomb, states that the force exerted by

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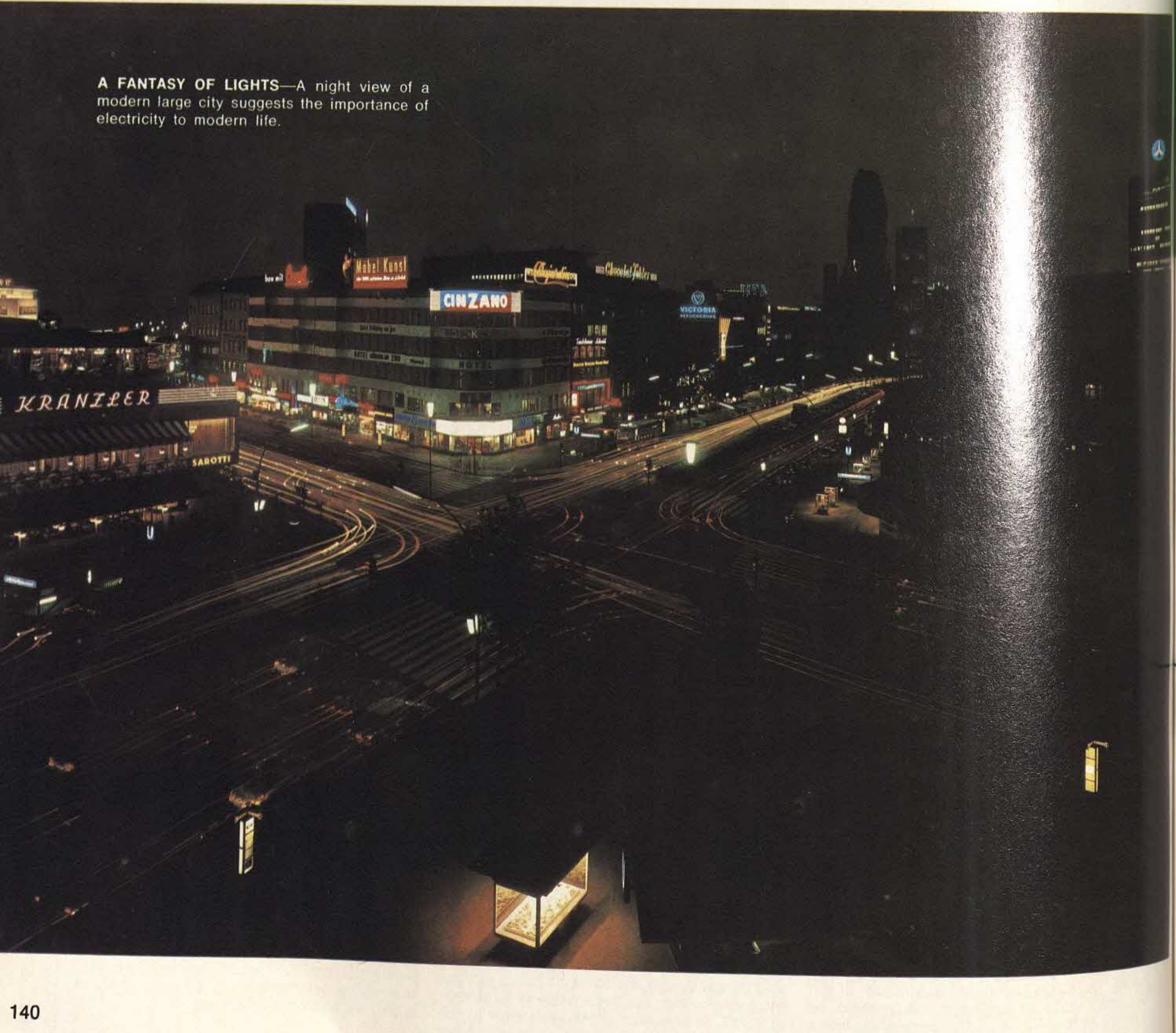
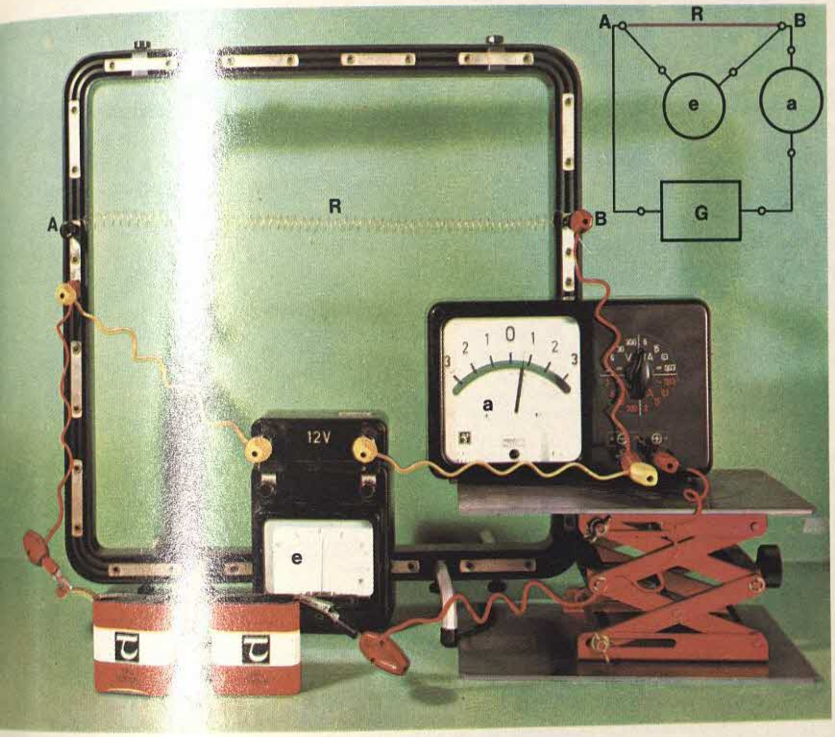


A FANTASY OF LIGHTS—A night view of a modern large city suggests the importance of electricity to modern life.

2

a



b

SUBSTANCE	SPECIFIC RESISTIVITY ρ (ohm-meters)
silver	1.49×10^{-8}
copper	1.56×10^{-8}
aluminum	2.56×10^{-8}
zinc	5.60×10^{-8}
iron	9.00×10^{-8}
antimony	37.00×10^{-8}
manganin	42.00×10^{-8}
constantin	49.00×10^{-8}
mercury	95.00×10^{-8}
bismuth	110.00×10^{-8}
electrolytic solution	$\sim 10^{-2}$
wood	$\sim 10^{5}$
glass	$\sim 10^{14}$
mica	$\sim 10^{15}$
fused quartz	$> 5 \times 10^{16}$

OHM'S AND JOULE'S LAWS — Illustration 2a shows an electric circuit and its corresponding circuit diagram. A voltmeter **e** is applied to the ends of the conductor **AB** to measure the potential difference. The instrument indicated by the letter **a** is an ammeter and measures the amount of current flowing in the circuit. Two batteries **G** ensure the flow of a constant current. With metallic conductors and electrolytic solutions, experiments have shown that current flows through a circuit in accordance with the following formula, called Ohm's first law, which describes the relationship between the current in segment **AB** of the circuit and voltage between the ends of **AB:**

$$V_A - V_B = Ri.$$

The constant **R** depends on the dimensions and the physical state and type of material used. **R** is called the resistance of the segment **AB** of the circuit and is given by the following formula, called Ohm's second law:

$$R = \rho l/s,$$

where **l** and **s** are, respectively, the length and cross-sectional area normal to current flow in the segment **AB** of the circuit, and ρ is the specific resistivity.

The table in Illustration 2b gives the specific resistivity of various substances. Substances with low specific resistivities are good conductors of electricity; those with high specific resistivities are dielectrics or insulators. The specific resistivity usually varies not only with the substance but also with temperature. Conductors whose resistance does not vary much with temperature are used as standards of resistance. The two in this table that can be so used are manganin and constantin, a nickel-copper alloy. The variation of the resistance of pure metals and the accuracy with which these variations can be measured have been used to construct resistance thermometers. Two examples of these are pyrometers, which measure extremely high temperatures, and bolometers, which measure extremely small temperature changes.

Superconductivity is a phenomenon associated with the variation of resistivity with temperature. At extremely low temperatures resistivity almost completely disappears and an induced current will flow for hours in a circuit without requiring replenishment of energy.

The power **W** available in the circuit—that is, the work performed by the electricity in the segment **AB** of the circuit in a unit time—is given by Joule's law:

$$W = (V_A - V_B)i - i^2R.$$

This energy is developed in the circuit and can be usefully applied as in heating elements, for example. In other situations production of heat may cause unwanted loss of energy.

one charge on another is proportional to the product of the quantity of electricity that each charge possesses divided by the square of the distance between the charges.

A simple device—the capacitor (or condenser)—is important to the study of both static electricity and electric currents. The capacitor permits an electrical charge to be easily stored. In its simplest form, a capacitor consists of two surfaces placed face to face but insulated from each other. The surfaces are usually flat or rolled into a cylinder and are commonly referred to as the plates of the capacitor. In practical applications, a cylindrical shape is generally preferred as it occupies a smaller volume for any given area of capacitor surface. As the surfaces are insulated from each other, a difference in potential exists between them. The amount of this difference depends on the distance between the surfaces and the quantity of electric charge stored on them. If the two faces of the capacitor are connected by a conductive wire, this potential difference will be neutralized by a migration of charges from one face to the other. Such a migration of charges is called an electric current, and the capacitor is said to discharge during this neutralization. Furthermore, whenever two regions of unequal potential are connected by a conductor, an electric current is obtained. This current continues as long as the potential difference between the two regions exists. A material that permits the flow of current (migration of charge) is called a conductor.

Because metals are usually good conductors, they are most often used in electrical circuits. Other materials, called dielectrics (insulators), prevent the flow of electric current. Insulators are used, as their name implies, to shield personnel or parts of equipment from electric current.

In order to study electric current, certain quantities must be defined. One of these is the intensity i of an electric current. In contemporary writing intensity is referred to simply as current, which is a measure of the number of charges that pass through a section of a conductor in a unit time interval. Average current is defined by the equation

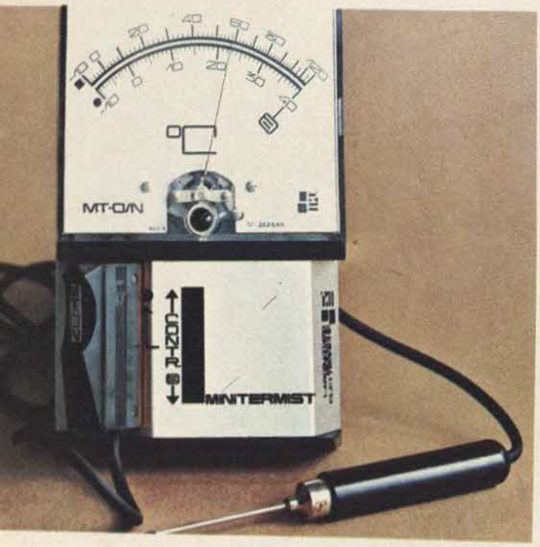
$$i = Q/t,$$

where Q is the quantity of electric charge and t is the time that elapses while the charges are passing along the conductor. The current flowing at any instant is defined as the result of the limit obtained when the elapsed time is infinitely small. In the case of a capacitor, the average current can be determined if the charge originally on the plates is known and the time that passes before the capacitor is completely discharged is measured. Such a value of the current is only an average; because the passage of the charge causes the potential difference between the two faces to diminish, the value of the current at any given time is proportional to the potential difference.

A current caused by discharging a capacitor flows only an extremely short time. To ensure that the current continues to flow between the two plates of the capacitor, a potential difference between the plates must be maintained. Potential difference is commonly called voltage, as the unit of measure usually used to specify potential is the volt or some decimal multiple thereof. To maintain a voltage across the plates, devices called generators are employed. Whenever a constant voltage is maintained, the current that flows in the conductor will be constant with time. Such a current is called a direct current and the study of this type of current constitutes the theory of d-c electricity.

3

a



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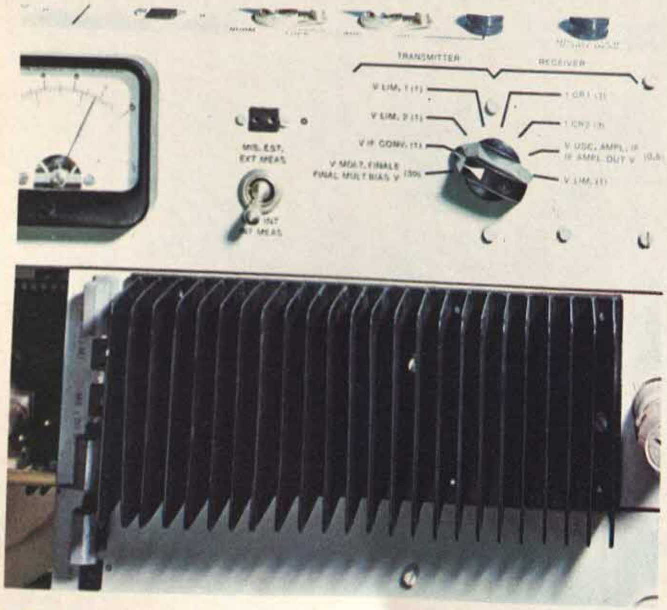
APPLICATIONS—Illustration 3a shows an instrument used for measuring temperature. Its operation is based on the fact that the resistivity of a conductor varies in a precise manner with temperature. Electrical power is supplied to the instrument to induce a current in the circuit. The amount of this current can be determined using Ohm's law. For a given voltage, cross-sectional area of the conductor, and length, this current must relate in a precise way to the resistivity of the conductor. As the resistivity is related to temperature, measuring the current at the same voltage permits indication of the temperature of the object being tested. Only a part of the power supplied to the electric motor of the train in Illustration 3b moves the train; the other part is dissipated as the motor heats up in accordance with Joule's law and as frictional losses occur. Illustrations 3c and 3d show where a loss of power occurs. Illustration 3c shows the heat sink of a large transistor. The heat is dissipated by large metal vanes. Illustration 3d shows an industrial transformer with a nucleus of elements cooled by an oil-circulated system.

c



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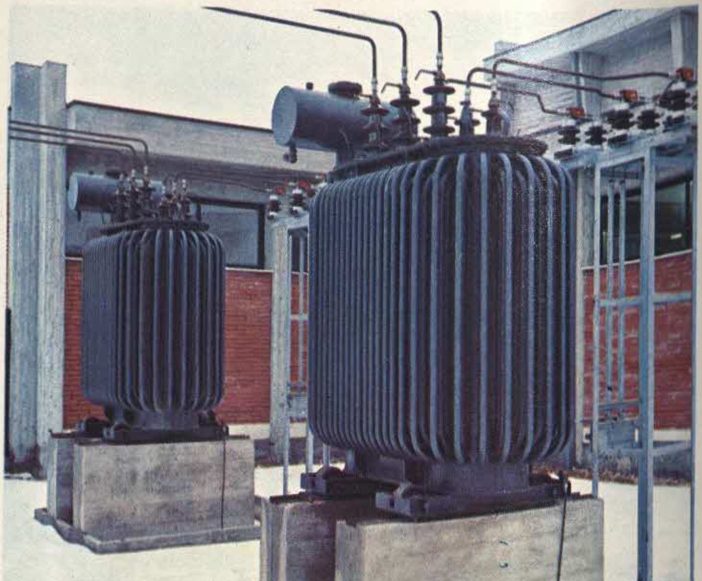

4

THE PRINCIPLE OF ALTERNATING CURRENT —Alternating current, a flow of charge which periodically changes its direction, can be explained simply. As already noted, direct current occurs only if the fundamental parameters —voltage and current—maintain a constant flow of electrical charge. On the other hand, if variable flow occurs, these parameters will vary according to certain mathematical laws. When the voltage and current vary periodically from positive to negative values, the current is called alternating (a-c). An examination of the current flow in a circuit containing a capacitor will clarify this concept.

Illustration 4a is a schematic diagram of a circuit that utilizes a generator **G** to supply the electromotive force **E**. An electromotive force is generated whenever a reversible transformation between electrical energy and some other form of energy takes place. The magnitude of an electromotive force may be defined quantitatively as the energy per unit of charge passing through the generator. It is specified in volts, the same units used to express potential difference. An ammeter **A** and a voltmeter **B** measure, respectively, the current and the voltage in the circuit at any instant. **C** is a capacitor that can have either a flat or a cylindrical face.

When the switch is closed, a current flows through the circuit until the capacitor is charged. The instruments **A** and **B** record the values of current and voltage at a given moment during the flow. Illustration 4b shows the variation of voltage and current with time until the capacitor is charged. Note that the voltage **V** increases gradually until it reaches a value **E** equal to the electromagnetic force of the generator, whereas the current **I** increases rapidly to a value **E/R** and then decreases gradually to zero.

After the capacitor is charged, opening the switch will retain the charge in the capacitor. However, if a short circuit occurs in the capacitor as a result of connecting a conductor across its two extremities, the capacitor will discharge. The current and voltage variation during this discharge is recorded by the instruments and is shown in the right-hand part of Illustration 4b. Note that the current now decreases from a negative, instantaneous value of **E/R** to zero, whereas the voltage decreases from a positive value **E**.

If this process of charge and discharge is repeated periodically, the sinusoidal variation of current **I** and voltage **V** (shown in Illustration 4c) results. A characteristic of this sinusoidal variation is that the maximum value of one quantity—either the positive or negative maximum—corresponds to the minimum value of the other. When this characteristic is evident, the current is said to lead the voltage by 90°. However, if a solenoid **S** is substituted for the capacitor in the circuit (Illustration 4d), the current and voltage values will change their relative positions and the current will lag the voltage by 90° as in Illustration 4e. In both cases it is correct to say the current and voltage are out of phase by 90°.

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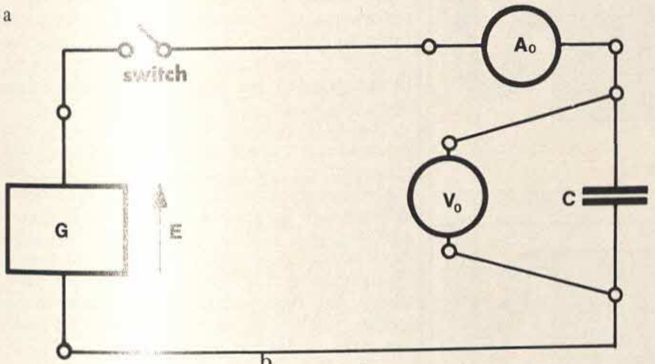

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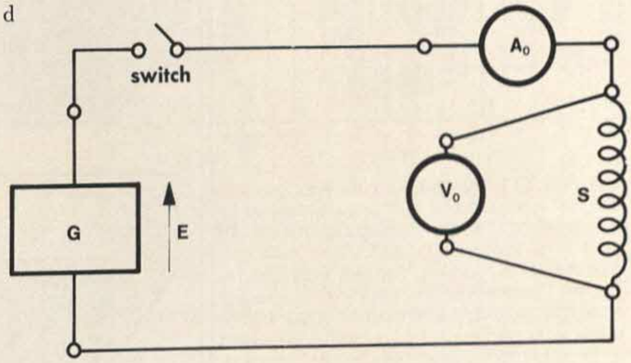

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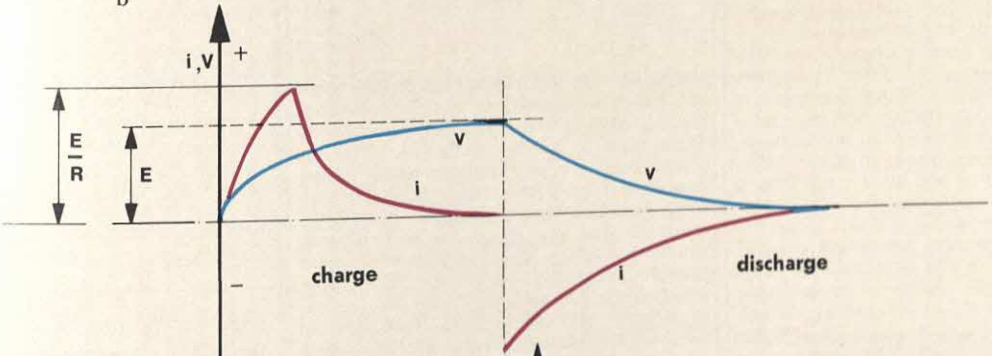

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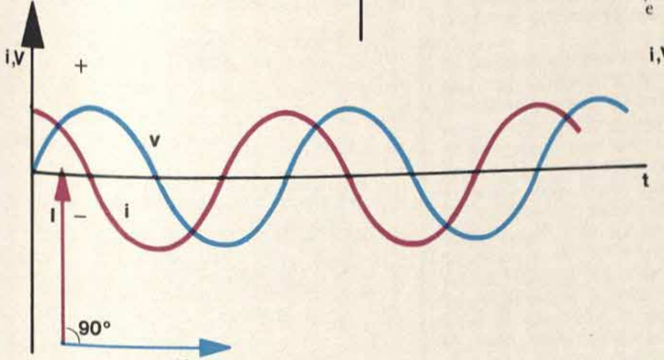

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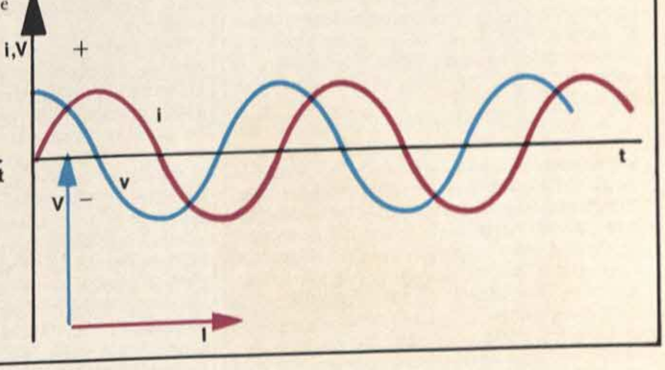

THE VOLTAIC EFFECT | producing continuous electric current

The ancient Greek philosopher, Thales, found that, if a piece of amber were rubbed with a cloth, it would attract certain lightweight objects such as wood fibers. Thales thus discovered static electricity, and he attributed the force to *elektron* (the Greek name for *amber*). Many experiments with static electricity followed this discovery. However, not until the eighteenth century was the production of truly continuous electric current possible. The Italian anatomist Luigi Galvani found that pieces of two different metals touching the nerves of the legs of

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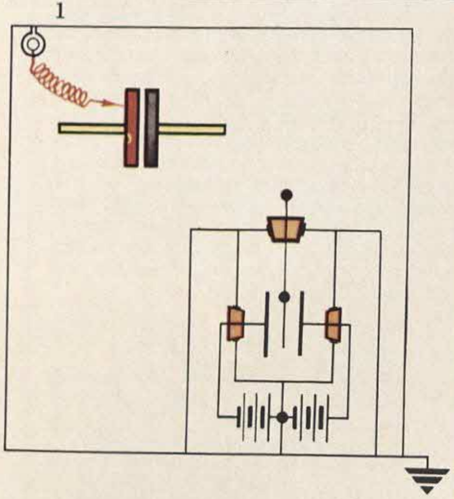

VOLTA'S EXPERIMENT—To demonstrate the difference of potential that is generated when two different metallic conductors are placed in physical contact with each other, Volta carried out an experiment that can easily be repeated. To assure the absence of electric potentials or fields not arising from the experiment, it is carried out in a container called a Faraday cage (after the English scientist, Michael Faraday). This electrically grounded container is made of conductive sheet (or mesh) metal. Two metal plates with insulated handles are placed inside the box. To replicate Volta's experiment, the plates are made of copper and zinc respectively, although some other metals would work just as well as these.

The two plates are placed in physical contact with each other and the copper plate is connected to the grounded wall of the containers. When the copper and zinc plates are connected, they become electrically charged. The device used in this experiment to determine the electrical charge is an improved version of the electroscope used by Volta. It consists essentially of a sheet of gold foil attached to a metal shaft that passes into the container through an insulating stopper. When a charged object touches the metal shaft, the sheet of gold foil is deflected. The amount of deflection is an indication of the amount of the charge.

To amplify the effect of a charge on the gold foil, it is flanked by two plates connected to the poles of a battery of cells, the center of which is grounded. Using this arrangement, an experimenter can easily see deflections of the gold foil caused by an electrical charge. Contacting the copper plate with the gold foil causes a visible deflection of the foil in one direction. Contacting it with the zinc plate causes deflection in the opposite direction. It follows that charges on both plates exist because of the contact between them and that the difference in potential across the copper-zinc cell is annulled by the mutual connection of the plates to ground.

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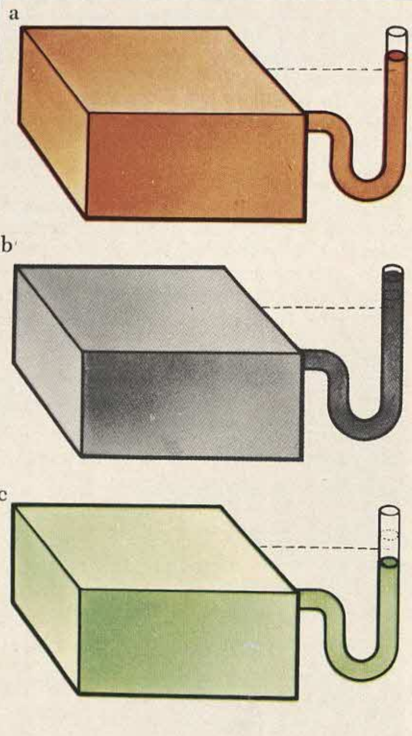


BASIS OF THE VOLTAIC EFFECT—The modern theory of metals and their atomic, molecular, and crystal structures provides an explanation of the Voltaic effect. From an atomic point of view, metals consist of crystal lattices in which atomic nuclei occupy essentially fixed positions and are surrounded by electrons that are mobile in all directions within the lattice. Only in instances where photoelectric, field, or thermionic discharge is effected do the electrons leave the lattice. In different metals electrons have different degrees of mobility; hence, different metals have different potentials for gaining or losing electrons.

This point can be illustrated by drawing an analogy between electrical potential and gas pressure. For this analogy three metals are used: copper, zinc, and platinum. If it were possible to place a kind of manometer inside the crystal lattice of each of these metals, and if the liquid level in the manometers were an indication of the gas pressure or electrical potential, the observations would be those noted above. The level reached by the manometer for the copper (Illustration 2a) is taken as the datum. The level reached by the manometer for zinc (Illustration 2b) is higher, and the level attained by the manometer for platinum (Illustration 2c) is lower. Accordingly, for each metal there is a standard electrical potential, and if two metals with different potentials are physically in contact, a potential difference exists across the junction.

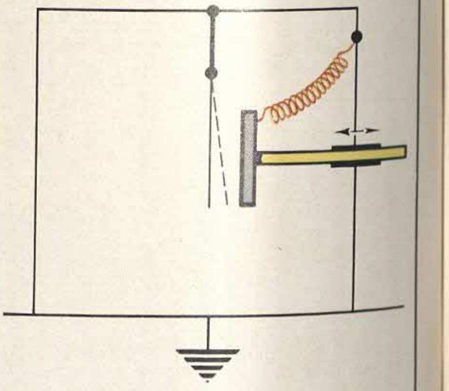
3

MAJORANA'S EXPERIMENT—After Alessandro Volta made his discovery many physicists made further studies of the Voltaic effect. One of these was the English chemist William Nicholson, who also invented a hydrometer in 1790. Another was E. Majorana, whose experiment was also conducted in a Faraday cage.

Inside the grounded, metal container Majorana placed a plate of some metal (copper, for example), in such a way that it could be moved and still be connected to the wall of the box. From the top of the box he suspended an extremely thin quartz thread that had been metallized with gold. The experiment involved slow and careful movement of the copper plate closer to the gilded thread. When the distance between the plate and the thread was very small—about 2 to 3 mm (about 0.08 to 0.18 in.)—the thread became strongly attracted to the plate because of the difference of potentials of the two metals, gold and copper. The Voltaic effect resulted from the electrical connection of the copper plate and the gilded thread to the same conducting walls of the box. Had the thread been metallized with copper instead of gold, no attractive force would have existed, because the difference in potential between the plate and the thread bearing the same metal would have been lacking.

The Voltaic effect can also be demonstrated by means of a quadrant electrometer in which the quadrants are made of different metals and are arranged in a suitable order. A potential difference is established between the moving part and the quadrants; this potential difference keeps the moving part oriented toward the quadrants. The electrometer shown (Illustration 3b), however, is used to measure potential differences; the quadrants, therefore, are made of the same metal.

a



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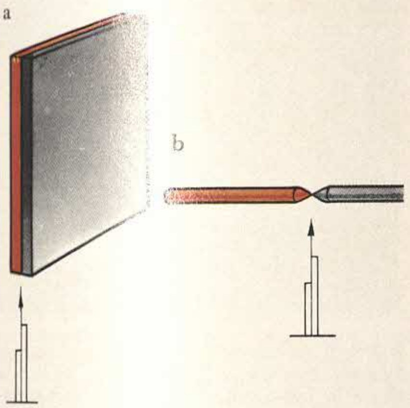
THE FIRST LAW OF THE VOLTAIC EFFECT—Two laws are associated with the Voltaic effect. The first law states that the potential difference between two conductors depends on the nature of the conductor only, and not on the shape, size, or orientation of the conductors. Two large metal plates (Illustration 4a) that are in contact with each other over the entire extent of their surfaces result in the same potential difference as two other forms of the same conductors (Illustration 4b) that are smaller and touch each other only at a single point. The bar charts below the two illustrations emphasize the fact that the difference of potential across the two configurations is exactly the same.



This point calls to mind an analogy between potential and hydrostatic pressure of a gas. If two vessels filled with gases at different pressures are connected, the difference in pressure is the same regardless of the size of the vessels and the size of the channel between them. However, other factors have bearing on the difference of electrical potential between two conductors made of different metals. Among these factors are the dielectric constant of the medium between the conductors, the presence of impurities on the contact points or surfaces, and impurities in an electrolyte. The last of these factors is important because certain impurities in an electrolyte may actually form separate cells with either or both of the conductors in the cell. Cleanliness of conductors and purity of electrolytes is essential for the maintenance of constant and accurate voltages in cells with extremely small potentials.

a frog caused muscular contraction if the ends of the metals were connected to complete a circuit. Soon after this discovery, another Italian scientist, Alessandro Volta, built an apparatus that produced continuous electric current and made possible scientific investigation of the laws determining the relationship of electricity and magnetism.

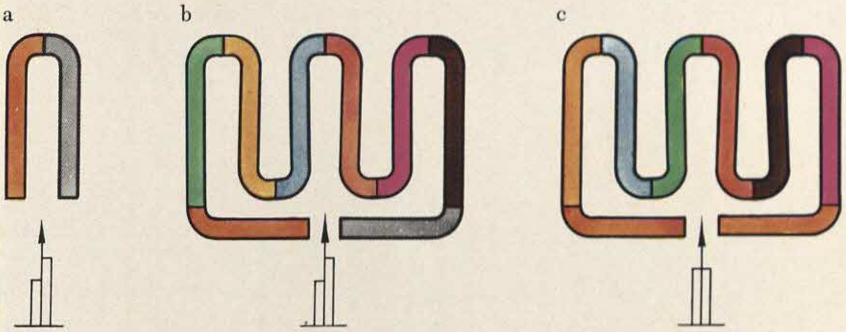
Volta's apparatus, called the Voltaic pile or battery, consisted of several cells placed in a line or in series. Volta later discovered a technique that could be used to produce a sustained flow of electric current for a long period of time. The technique involved using an acid solution as the medium between the poles of the cells.

5

THE SECOND LAW OF THE VOLTAIC EFFECT—The second law states that the difference in potential between two metals at the beginning and the end of series of connections between them depends only on the nature of the two metals—and not on the interposing conductors, in cases where no conductors of the second species are included in the series of interposing conductors.

As a consequence of this law, two conductors made of different metals and placed in contact with each other in the air (Illustration 5a) have a difference in potential that depends solely on their nature. In a second case (Illustration 5b), the same two metals are connected through a series of interposing metallic conductors, and they have exactly the same difference of potential. In a third case (Illustration 5c), two conductors made of the same metal are connected by a series of metallic conductors; however, because both ends of the series are of the same metal, no difference of potential exists between the ends of the chain. If such a series were actually constructed and connected, there would be no current because there would be no difference of electrical potential to drive electrons in any direction.

The statement of the second law of the Voltaic effect must be qualified: the law only applies if there is no difference in temperature at the two ends of the series of conductors. Inasmuch as a difference in temperature alters the standard potential of a metal, if two conductors of the same metal are connected at different temperatures, a difference of potential will exist. This is known as the thermoelectric effect and is the basis of operation of the thermocouple.



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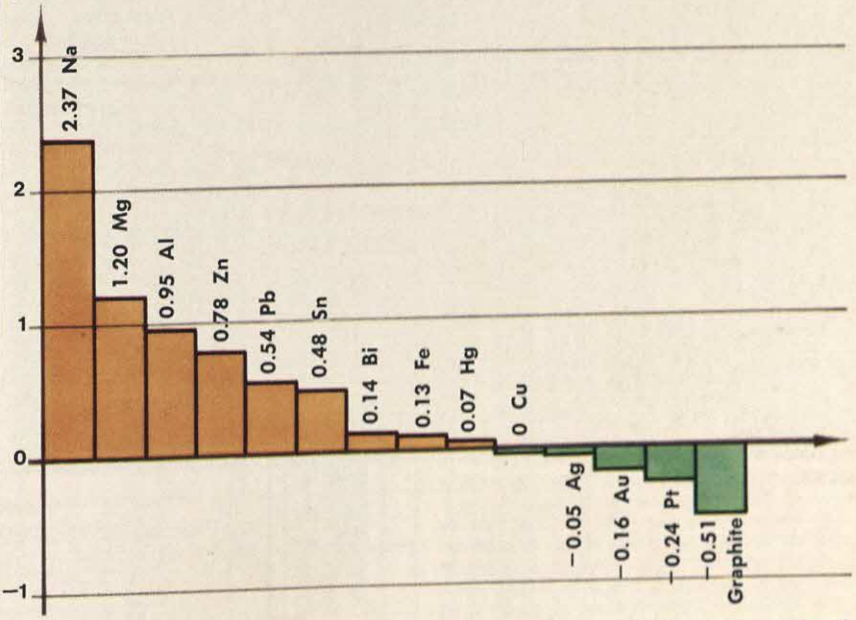

THE VOLTAIC SERIES—For every metallic conductor at a given temperature, a given standard potential exists and can be used to calculate its difference of potential with any other metallic material. The system that has been adopted is to use pure hydrogen as the standard because it forms an extremely stable electrode whose potential is at a convenient value with respect to other metals. All other metals are related to hydrogen by the potential difference set up between them and the normal hydrogen electrode. To calculate the potential difference between any two metals, lead and iron for example, the differences of their potentials with respect to hydrogen are determined and the lesser one is subtracted from the greater one as follows:

$$V_{Pb,\,H_2} - V_{Fe,\,H_2} = V_{Pb,\,Fe}\,.$$

Tables provide the data to be used in this equation, and application of the equation gives the potential difference being sought.

$$0.54 - 0.13 = 0.41.$$

PHOTOELECTRICITY AND PHOTOCELLS

exposure meters and quantum mechanics

In 1887 the German physicist Heinrich Hertz, while trying to prove the existence of radio waves, discovered the photoelectric effect—the action by which certain substances give off free electrons, or electricity, as a result of absorbing light energy.

In 1902 Albert Einstein advanced the hypothesis that, in order to explain the photoelectric effect, it was necessary to assume that light is corpuscular—that is, composed of particles. Max Planck already had suggested, in connection with the radiation of black bodies, that it was necessary to imagine light as being made

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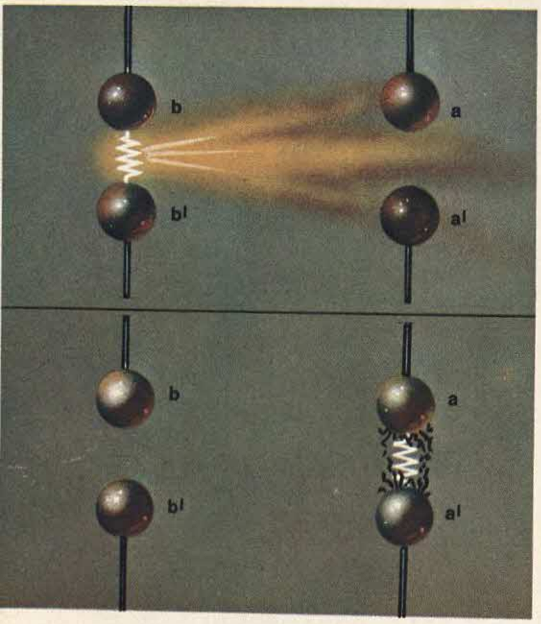

DISCOVERY OF THE PHOTOELECTRIC EFFECT—In 1887, Heinrich Hertz, in studying the conditions under which an electric spark could be discharged between two spheres, **a** and **a'**, discovered that no spark occurred if the electric potential between the spheres did not reach a certain strength. If, however, a spark was discharged between a neighboring pair of spheres, **b** and **b'**, a second spark was discharged between **a** and **a'**, even though the electric potential between them remained insufficient. Hertz supposed that the light emitted by the discharge of the spark between **b** and **b'** helped cause the second spark because it struck the surfaces of the metal spheres and the air between them. In particular, he surmised that the light radiation of the first spark caused electrons to be emitted both from the surfaces of the spheres and from the molecules of the air.

In the following year German physicist Wilhelm Hallwachs took up and extended the study of this phenomenon, which was later given his name. Some texts still speak of the photoelectric effect as the Hallwachs effect.

THE SURFACE BARRIER OF METALS—A metal consists of a crystal in which the atoms occupy clearly defined positions, although not all of the electrons that belong to these atoms are bound to them. The electrons are in a state of more or less neutral equilibrium and are free to move inside the metal if attracted by external electric or magnetic fields. If, however, the electrons reach the surface of the metal, they are driven back toward the interior. In fact, the surface of the metal is made up almost exclusively of electrons. A little below these is a first layer of positive nuclei with insufficient electrons to equalize the charge of the nuclei. The electrons that reach the surface, situated as they are between a negative external stratum and a positive interior one, are driven back inward and do not, under normal conditions, emerge from the surface of the metal. If the metal is heated, the electrons are jolted by the atoms that are vibrating because of the heat and are violently accelerated. If they reach the surface with sufficient velocity, the electrons may break through the surface barrier. This phenomenon is known as the thermionic effect. Electrons may also be driven out of the metal when it is struck by light rays or electromagnetic radiation in general. The expulsion of electrons by heat is known as the thermionic effect, while expulsion caused by light is known as the photoelectric effect.

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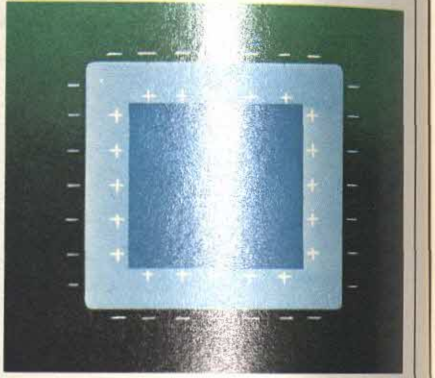

STUDYING THE PHOTOELECTRIC EFFECT—The apparatus used for studying the photoelectric effect consists of a vacuum tube or chamber **a** that contains a metal sheet **b,** used to study the surface emission of electrons. In order to illuminate the surface of the metal to the required intensity, the radiation used must be able to pass into the tube. Therefore, the tube contains a window **c** that is transparent to the radiation used. If the photoelectric effect produced by ultraviolet rays is to be studied, the window may be of quartz. Opposite the metal sheet is a metal rod **d.** The metal sheet and the rod are connected to a battery **e** by wires passing through the chamber, with the rod connected to the positive pole and the metal sheet to the negative. When the metal sheet is sufficiently illuminated by light from the window, it emits electrons that are attracted by the rod, then conducted into the battery and back through it to the metal sheet. The circuit continues as long as the metal sheet is illuminated. To measure the number of electrons in circulation, which depends on the frequency **f** of the radiations illuminating the emitting surface, an instrument is required that will detect very low currents. A galvanometer **g** is normally used.

Although this apparatus is theoretically simple, it needs to be constructed with the utmost care: the tube, or chamber, must be emptied of air because the movement of the electrons would otherwise be obstructed by the molecules in the air, or the presence of air might increase the electric charge. The surface of the metal sheet must be free of impurities because even a few foreign atoms would be sufficient to impede the regular emission of electrons and thus affect the whole process.

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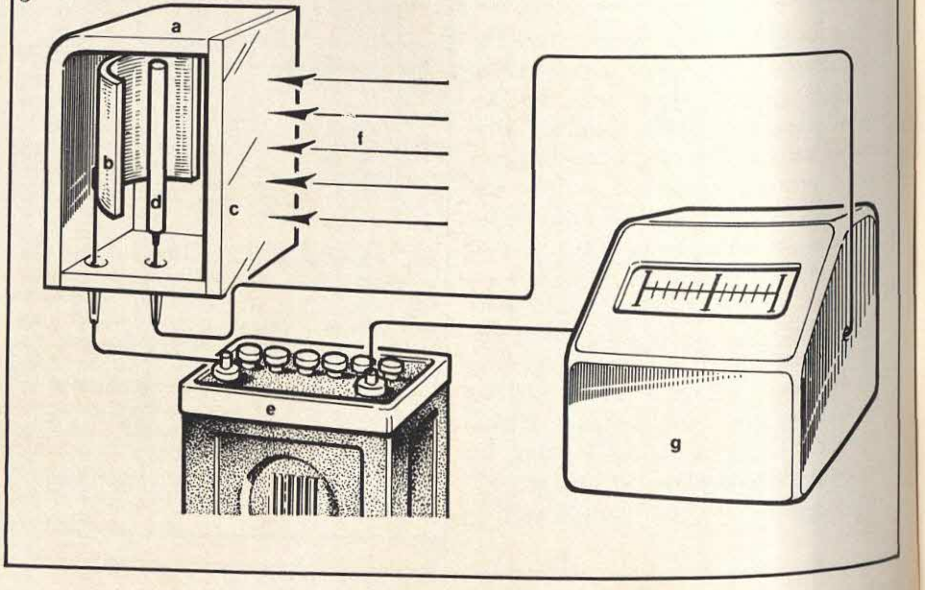

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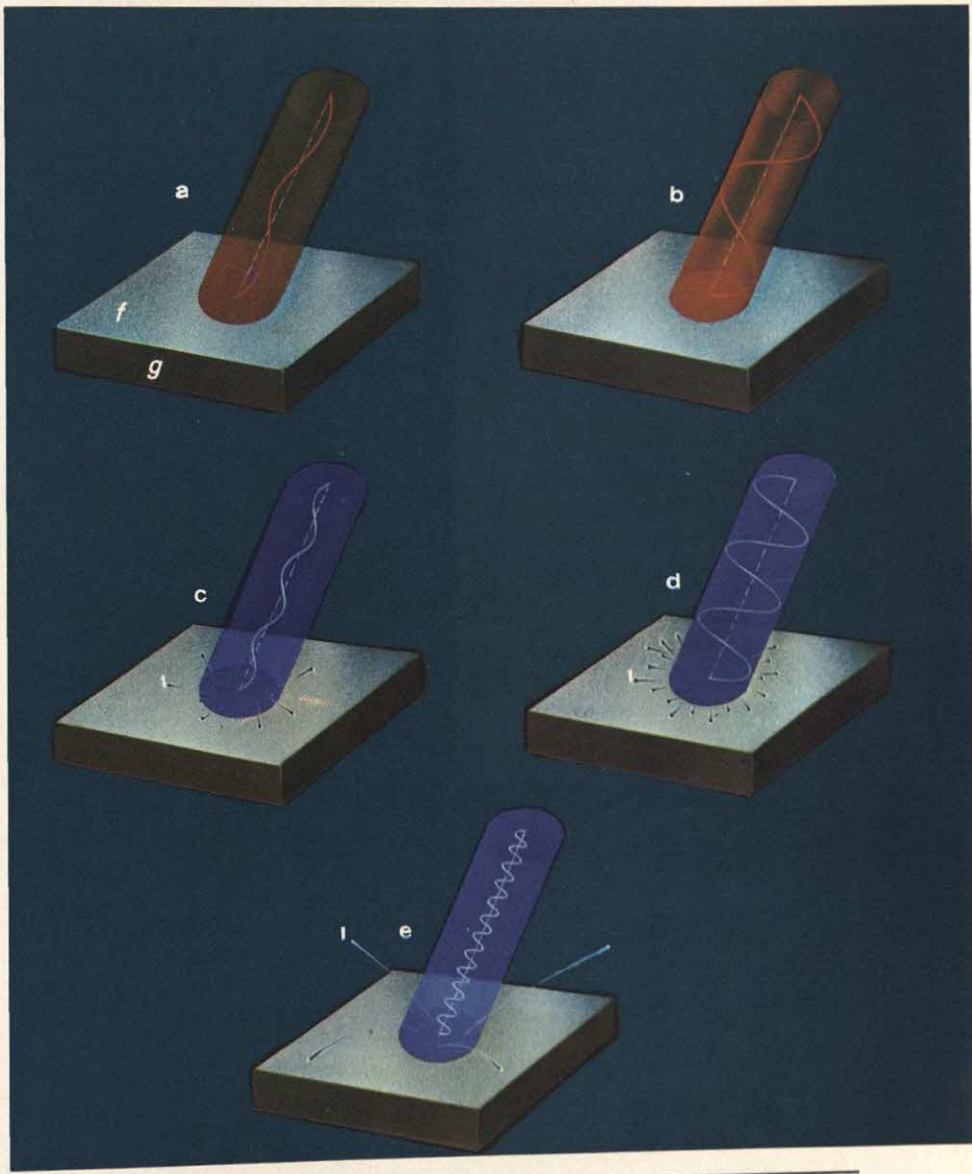

THE THEORY OF THE PHOTOELECTRIC EFFECT—Before explaining the mechanism of the photoelectric effect, it is necessary to know the fundamental laws that regulate it. In Illustration 4a, a metal surface **f** is illuminated by a weak red radiation (assuming the metal sheet to be inside a glass tube as described in Illustration 3). No electrons will emerge from the metal g. According to the classical theory, when the intensity of the radiation is increased (Illustration 4b), the metal surface will be bombarded by electromagnetic waves that can be imagined as sinusoidal and greater in intensity than those in 4a. Regardless of the amount of increase in the intensity of the radiation, however, electrons are still not emitted from the surface of the metal.

Where both the intensity and the wavelength of the radiation are diminished (Illustration 4c), the radiation will become first yellow, then green, blue, then violet. Weak though it is, when it becomes violet, electrons **I** will begin to emerge from the metal surface. If the intensity of the radiation is increased (Illustration 4d), more electrons will emerge. If the energy with which the electron emerges from the surface of the metal is measured, it will be found to be very weak: the electron departs at a low velocity.

If the wavelength is diminished still further (Illustration 4e) and the intensity of the radiation kept constant, the number of electrons emerging from the metal does not increase. What does increase is the energy of each electron. By diminishing the wavelength, which was violet, the radiation becomes ultraviolet, and ultraviolet rays are invisible.

The photoelectric effect is subject to the following laws:

1. Electrons are emitted only when the wavelength is suitable. Electrons are emitted from any metal under ultraviolet rays. As radiation proceeds through the range of visible rays toward red, the number of metals in which this effect is produced gradually diminishes.
2. The energy of the electrons emitted depends on the wavelength of the radiation striking the metal; the shorter the wavelength, the greater the energy of the liberated electrons.
3. The number of electrons emitted by the metal is proportional to the intensity of the radiation.

up, not of continuous waves, but of a large number of particles known as quanta, or photons, each having an amount of energy determined by the frequency of radiation multiplied by a universal constant h, now known as Planck's constant. According to this hypothesis, the higher the frequency of radiation and the shorter the wavelength, the greater the energy of the photon. (Wavelength is inversely proportional to frequency.)

The photoelectric effect takes place, for example, when a metal surface is bombarded with high-energy photons—those having a short wavelength. Provided it has sufficient energy, each photon can liberate an electron.

In freeing an electron, the photon is destroyed. A portion of its energy helps the electron break through the barrier of the metal surface (the effectiveness of the barrier differs from one metal to another); the remainder of its energy increases the velocity with which the elec-

PHOTOELECTRIC CELLS FOR COMMERCIAL USE—As shown at the left, a photoelectric cell consists of a glass vacuum tube mounted on an insulated socket from which protrude the metal pins that conduct electric current into the cell. Light passes into the tube and illuminates a metal sheet within the tube. Electrons are emitted from the metal sheet as the result of the photoelectric effect. Opposite the sheet is a positively charged metal rod that collects the electrons emitted from the metal sheet.

The rod and sheet are charged through the metal pins. At the right is shown in outline a beam of light illuminating the surface of the metal sheet. This light supplies energy to the electrons in the surface stratum of the metal, enabling the electrons to overcome the surface barrier and emerge from the metal.

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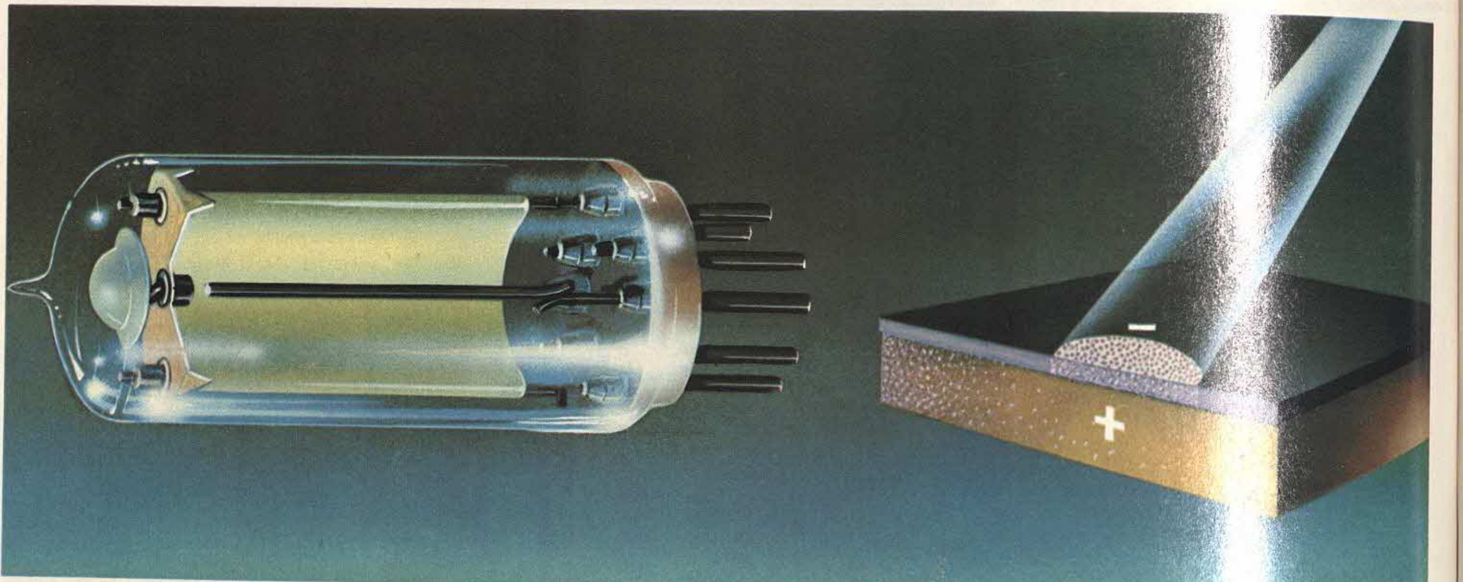

tron leaves the metal.

This fact may be expressed by Einstein's photoelectric equation:

$$\frac{1}{2}\, mv^2 = hf - P,$$

where $1/2\, mv^2$ is the kinetic energy with which the electron leaves the surface of the metal, h is Planck's constant, and f is the frequency of the radiation. Thus, hf is the energy of the photon and P the extraction potential of the electron, or the energy required for it to leave the surface of the metal.

Einstein's equation was not confirmed until 1906, when the American physicist Robert Millikan conducted experiments that verified Planck's quantum theory of radiant energy.

Another example of the photoelectric effect is a ray of light striking the human body, from which the light is able to extract electrons. The photoelectric effect, however, does not take place with all kinds of radiation: visible light is usually not able to produce it, but it is produced by the ultraviolet radiation of the sun.

In physics, the photoelectric effect is understood to mean the extraction of electrons from matter through light. However, it is necessary to distinguish between two types of photoelectric effect. The first is produced by either visible or ultraviolet light and causes the emission of the electrons from the surface of metal bodies. The second is caused by such radiations as gamma rays, which have a much shorter wavelength than ultraviolet or x-rays and can liberate not only surface electrons—those that are free or rotating on the periphery of the atom—but even detach from their atoms the electrons closest and most strongly bound to the nucleus. This second kind of photoelectric effect differs from the first only in its contribution to the study of atomic structures.

Lastly, the photoelectric effect has resulted in the development of instruments used to detect the presence of electromagnetic radiations by transforming light into electric current. Such instruments range from the common photographic exposure meter to the ultrasensitive instruments used by astronomers to measure the light of the stars. Other practical applications of the photoelectric effect include instruments for the determination of x-ray and gamma ray intensities, quality control in manufacturing, and the production of sound for motion pictures. In television production, the photoelectric effect is used to convert the light reflected from the object to be televised into an electric current. At the receiving end, a cathode ray tube (picture tube) utilizes the photoelectric effect to produce a picture on the face of the tube.

The laws governing the photoelectric effect provide an open window on the atomic world, helping scientists understand why the laws of classical mechanics are inadequate to explain atomic phenomena. The photoelectric effect can be explained only by adopting the hypothesis that light radiation is corpuscular as well as undulatory. This hypothesis is fundamental to the development of a system of mechanics that explains all the phenomena of atoms—quantum mechanics. The photoelectric effect thus is an introduction to the study of the following subjects:

1. The mechanism of the extraction of electrons from matter;
2. The technique for constructing photocells—the instruments to detect the presence of electromagnetic radiations by transforming them into electric impulses; and
3. The fundamental concepts of the quantum theory of radiation.

ELECTRIC CHARGE AND FLUX

sparks from a Ruhmkorff coil

Experiments performed with electric discharges produce interesting—even fascinating—results. Such experiments also yield important information. Electric discharges are a particular form of the passage of electricity through gases and hence have a large number of applications in science and technology. The experiments illustrated and described in this article are relatively simple, but they should be conducted with caution to guard against the dangers of high voltages.

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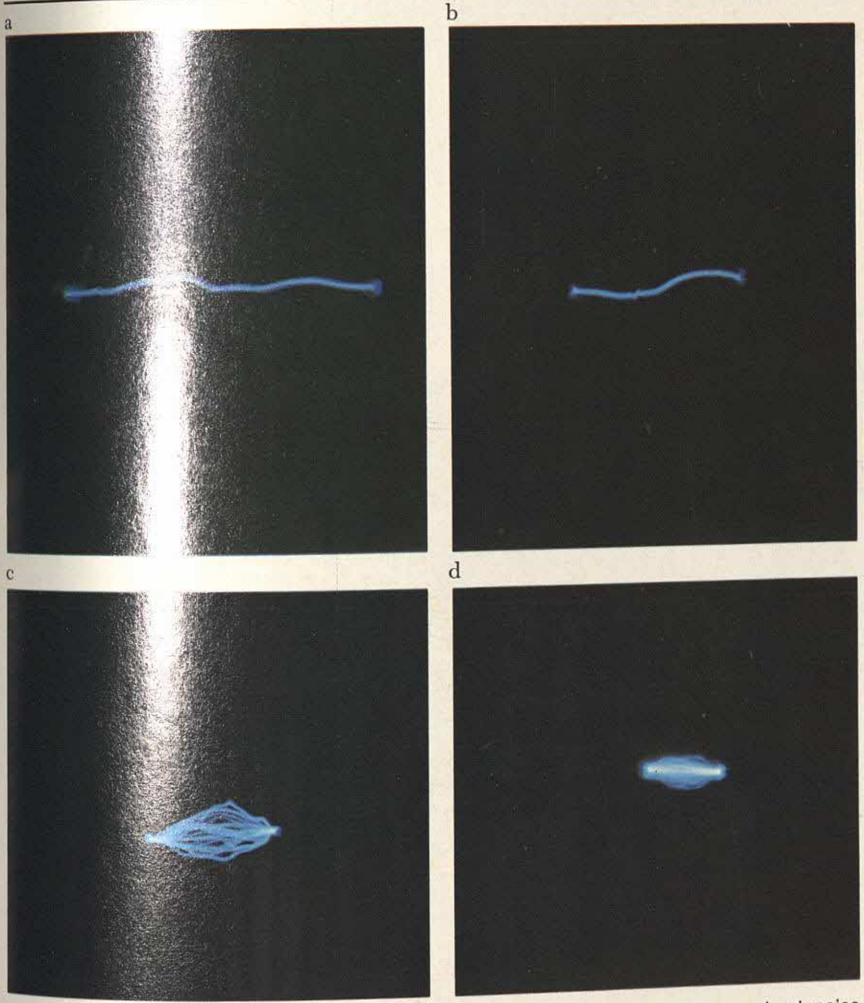

A SPARK BECOMES AN ELECTRIC ARC—If the terminals of the secondary circuit of a Ruhmkorff coil are connected to two electrodes and then moved apart until the longest spark possible is obtained, the resultant discharge is called a spark—a discharge maintained solely by virtue of the high potential between the electrodes, and set off only by a high potential difference between the electrodes. This type of spark is a miniature stroke of lightning (Illustration 1a); it is violet in color, rather thin and winding, is accompanied by the noise of a weak explosion, and is weakly luminous. On the other hand, if some capacitances are placed in parallel with the secondary circuit of the Ruhmkorff coil (and this can readily be done by gluing tinfoil to a plate of glass) the charge will condense, the voltage difference between the two electrodes will diminish, and the spark will only occur if the electrodes are brought closer together. The spark is now accompanied by a loud noise. When discharge occurs under these conditions, the air is heated so rapidly that its violent expansion sets up a sound wave as shown in Illustration 1b. Illustrations 1c and 1d show how this spark gradually changes into an arc. The more the capacity in parallel with the electrodes is increased, the closer the discharge comes to forming an arc.

The electric current that passes in an arc is much greater than that that flows in the first type of discharge described. The spark thus becomes transformed into a flame that has an extremely high heat capacity and that causes the evaporation of metal from the electrodes. This evaporation, in turn, causes the discharge to become colored. The discharge itself now has the form of a flame and no longer that of a spark. For this reason, the winding form shown in Illustration 1a does not occur.

2

GLOW DISCHARGE—If the secondary circuit of the generator is arranged in such a way that the electrodes are further apart, or if they are kept close but separated by a plate of glass, then the spark can no longer occur. All the same, an electric field is still present and acts on the ions present in the air. These ions are set in motion and result in the so-called "electric wind." The air that is crossed by this flow of ions glows with a characteristic violet color. The glow discharged almost gives the impression of a luminous fluid coming out of the electrode. Sometimes this discharge will also contain fine sparks that seem to branch off from the main stream.

An electric discharge is simply the passage of electricity through a gas. Electric discharges can also occur in a vacuum; in such cases only electrons will pass between the two electrodes. These electrons are obtained from the conducting bands of the metal used and pass from one electrode to the other by following the isodynamic lines of the electrostatic field.

In the most common cases, the electric discharge consists of ions and electrons moving in an ionized gas. Ionization, therefore, lies at the basis of the phenomenon of discharge. The phenomenon of setting off an electric discharge is particularly important when dealing with those discharges that are made to occur in a controlled manner and are set off by the passage of an ionizing particle. Discharge occurs when the potential difference existing between the two electrodes is great in comparison with the distance that separates them. The ratio between the potential difference and the distance is called the field; the intensity of the field determines whether or not a discharge can take place.

Consider a gas consisting of atoms—or neutral molecules—that are not subject to the attraction of the field. This gas probably contains a few ions and electrons that may have been produced by the passage of a particle of cosmic radiation, by terrestrial radioactivity, or by the spontaneous dissociation of an atom (although this is actually caused by a violent collision). Such an electron may accelerate sufficiently between collisions to enable it to ionize the atom that it strikes. This results in the production of a second electron, then a third, and so forth, with consequent multiplication that is extremely rapid. In the end, an almost complete ionization of the gas occurs, causing it to become a conductor.

3

EXPLOSIVE DISTANCE AND FLAME—The explosive distance is the maximum distance between electrodes from which it is still possible to obtain a spark. The explosive distance varies primarily as a function of the voltage difference, but it also depends on the shape of the electrodes. If both these parameters are left unchanged, it is possible to increase the distance between the electrodes if the air between them is ionized. This can be done, for example, by introducing an alcohol flame. This ionization will greatly facilitate the discharge, which will now become many times longer than it was in cold air. Because this experiment is relatively dangerous, the experimenter must neither come close to the flame nor touch it with conductors. In fact, it is not even advisable to touch the dish in which the alcohol-soaked cotton is burning, whether it is touched with the bare hand or with a conductor, because a part of the discharge could branch off from the principal spark—with serious consequences for the experimenter.

It should be noted that the spark becomes wider and less luminous when it crosses the flame (which is only slightly luminous because complete combustion of carbon takes place). In fact, since the spark is wider, it will also tend to be less hot and consequently less luminous.

During the nineteenth century, electric discharges opened the door to the study of atomic physics; in fact, electric discharges first demonstrated the existence of electric charges in atoms and subsequently made it possible to discover the electron and x-rays. However, these results could only be obtained after carrying out experiments under perfectly controlled conditions and above all, at low pressures. The knowledge obtained subsequently became useful in certain fields of technology and instrumentation.

The electric current that passes through the ionized gas is supplied by an input circuit. The electric energy is dissipated in the small volume of gas in which the discharge occurs; this dissipation produces a considerable heating of the small mass of gas, which becomes luminous.

If the electrodes are close to insulating surfaces, the state of cleanliness of these surfaces has a considerable influence and may enable the discharge to take place along the impurities deposited on the surface. In a case where an insulator does not resist the voltage and becomes perforated, the hole formed in the dielectric will be extremely small and regular, and its edges will be metallized. If the pressure of the gas is lowered where the discharge is made to occur, the explosive distance (that is, the maximum distance between the electrodes at which a discharge may take place) will be greater than it is at ordinary pressure. These experiments can also serve as the starting point for other interesting observations in the field of atomic physics. An example is the production of emission spectra of a gas (and the observation of them through a spectroscope) to demonstrate the presence of a high degree of ionization in the atoms of the gas in which the discharge takes place. It is also interesting to note that each gas emits a characteristic spectrum different from the one obtained by burning the same gas in a flame; the excitation potential is less in the flame than in an electrical discharge and, thus, produces lower levels of ionization.

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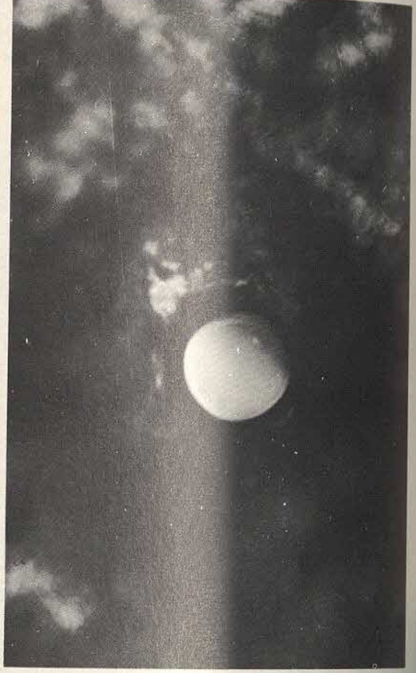

PERFORATION OF THE DIELECTRIC—When a dielectric is placed between the two points of a spark gap, a kind of insulating effect is produced. Consequently, the spark is prevented from jumping across the gap. However, the spark can only be prevented if the insulating material is sufficiently thick. If the layer of insulating material is too thin, the dielectric will be perforated and the spark will pass through the hole formed. The size of the hole formed by the passage of the spark is minimal—a few tenths of a millimeter. This hole is perfectly round, or at least this is the case if the properties of the dielectric are not excessively anisotropic. This illustration shows a hole produced by the perforation of a dielectric by means of an electric discharge. (250 X) The hole is round and very small. Also, the rim of the hole has been slightly blackened—this is due to a deposition of material from the electrodes. The same material may also become deposited in cases where a discharge has skimmed the surface of a dielectric; it is, therefore, quite possible for a dielectric that has been struck by a discharge to lose its insulating properties. If insulation is needed, it is then necessary to change the defective dielectric.

The basic item of equipment required for these experiments is a Ruhmkorff spark coil, connected to electrodes or other simple pieces of apparatus.

5

EXPLOSIVE DISTANCE AND THE PRESSURE OF THE GAS—To determine the value of the explosive distance while varying the pressure of the air in which the spark is made to occur, a series of experiments is necessary. To carry out these experiments, a spark must be produced inside a tube from which the air has been removed or, at least, considerably rarefied. Illustration 5a shows how such a tube is prepared.

A glass tube **a** with a diameter of at least 4 cm (about 1.6 in.) and a length of at least 10 cm (about 4 in.) is used. A test tube from which the bottom has been removed may be used; the edge of the cut end is smoothed by heating it in a flame. The letters **b** and **c** indicate rubber stoppers with which the ends of the glass tube are sealed; **d** and **e** are electrodes (rods of glass or copper). A thin glass tube **f** passes through one of the stoppers and puts the inside of the larger glass tube into communication with the outside, while **g** is a rubber tube with which the apparatus is connected to a vacuum pump.

Illustration 5b shows the complete apparatus. There are two cheap methods for producing a vacuum that, although not complete, is sufficient to have an appreciable effect on the spark. One of these consists of using a water pump that is connected to a faucet from which water issues at a certain pressure; the other method consists of using the suction side of an aerosol apparatus. The rubber tube **g** in Illustration 5a can be throttled to allow for passage of a small quantity of air; this makes it possible to obtain a smaller vacuum than that that would be produced if the glass tube were connected directly to the pump.

If a rarefaction of the air is produced in the glass tube (in which the two electrodes have been placed) in such a way as to be at the explosive distance for air at ordinary pressure, the spark occurs without any difficulty. The spark will still be produced if the electrodes are set further apart, but will be more diffused than at ordinary pressure. Illustrations 5c, 5d, and 5e show the different sparks that will be obtained as the pressure is diminished. If the pressure falls to a hundredth or a thousandth of its normal value, or even less, the discharge is transformed into a luminescence that spreads over the whole of the gas in the tube—not only diminishing the brightness of the discharge, but also lessening the total luminosity. Finally, if a graph were plotted of the explosive distance as a function of the pressure, all the points would lie on a straight line.

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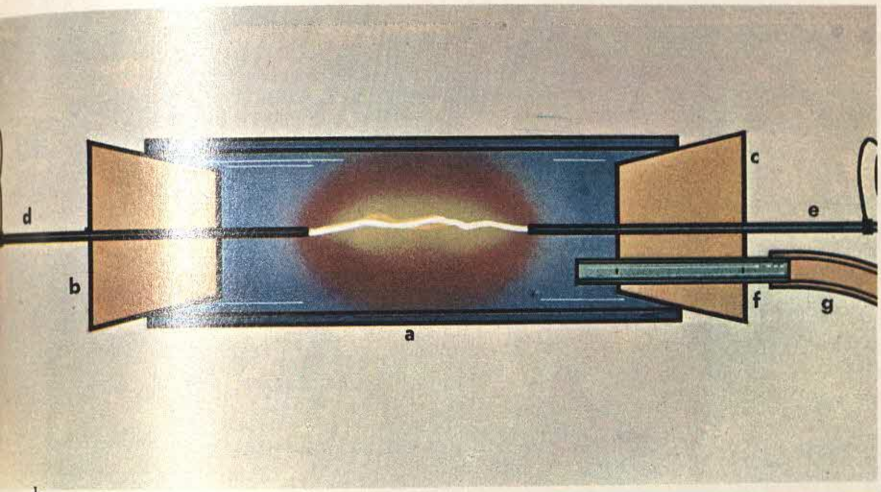

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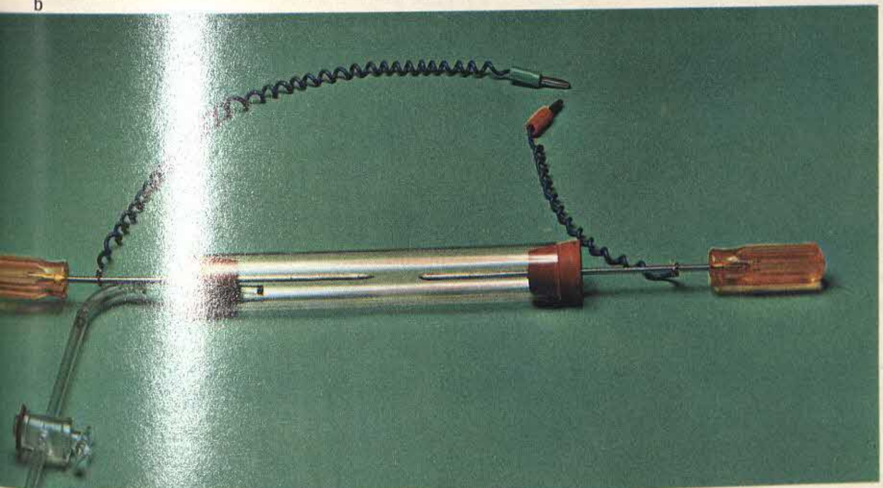

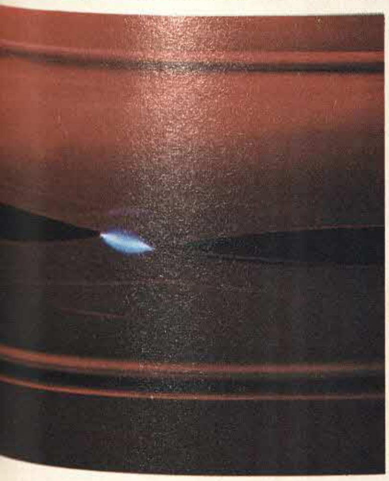

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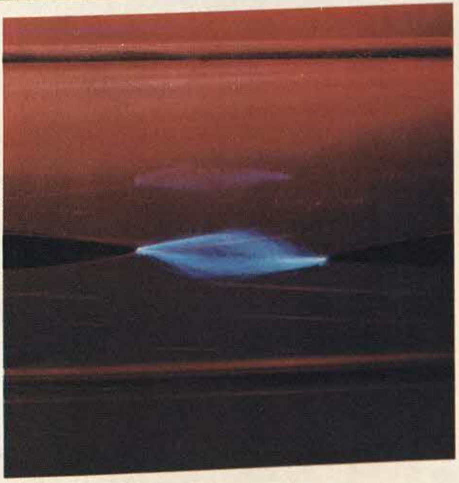

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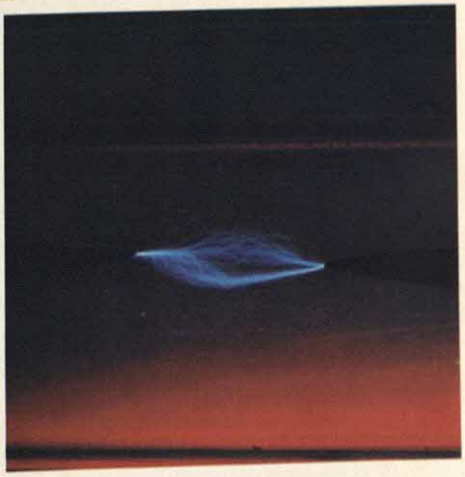

e

THE DIELECTRIC PROPERTIES OF SOLIDS | polarizability

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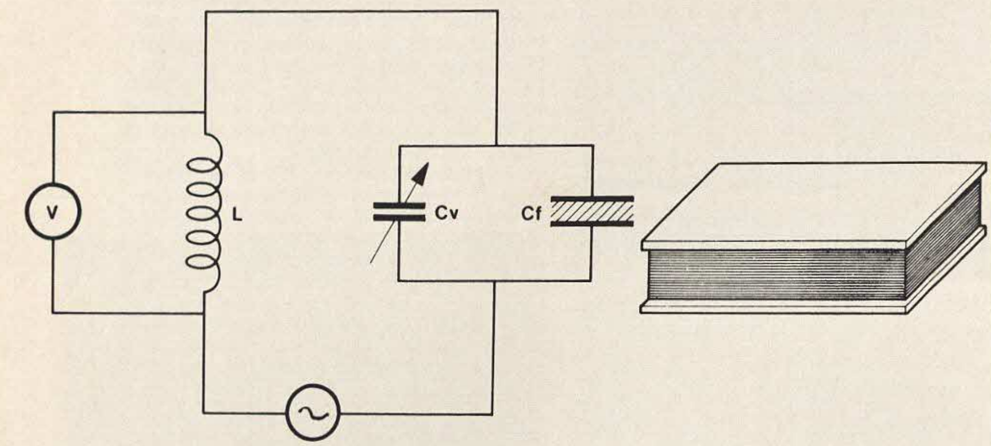


POLARIZABILITY AND THE DIELECTRIC CONSTANT—The polarizability of atoms and molecules in solids has the effect of varying the intensity of an applied external electrostatic field. For example, when two plates of a condenser are charged with a constant voltage, the field between them diminishes if the intervening space is filled with a polarizable substance. If a cavity is made in the dielectric —in the form of a thin needle positioned parallel to the direction of polarization (perpendicular to the plane of the condenser plates) —the field inside this cavity assumes a value represented by *E*, which is independent of the dielectric. Let *D* represent the average value of the field at a given point within the dielectric. The difference between *D* and *E* is equal to the value of the polarizability *P* multiplied by 4π: $D - E = 4\pi P$. The ratio D/E measures the dielectric constant (usually represented by ϵ).

Illustration 1 is a diagram of a circuit consisting of a parallel connection of an inductor **L** and two capacitors **Cv** and **Cf.** An ac voltage generator is included in the bottom side of the circuit; this generator is capable of generating a variable frequency. A voltmeter is connected across the terminals of the inductance, to measure the ac voltage across them. The circuit illustrated possesses a characteristic resonance frequency whose value depends on the value of the capacitance (on the right side of the circuit). The capacitance is again the sum of two capacitances: that of the variable condenser **Cv** and that of the fixed condenser **Cf.** The fixed condenser has its plates set a certain distance apart; a dielectric can be placed between them to measure its constant.

The relationship that connects the resonance frequency with the various magnitudes appearing in the circuit is expressed as follows:

$$\omega = \frac{1}{\sqrt{\mathbf{L(Cv + Cf)}}},$$

where ω is the resonance frequency and **L** is the inductance.

The resonance frequency is first measured when the condenser is empty. A dielectric is then placed between the plates of the fixed condenser and the variable condenser is adjusted to ascertain how much its capacitance must be varied to maintain the resonance frequency of the circuit at the same value as before. The numerical value of the dielectric constant can then be determined from this variation.

The arrangement illustrated permits determination of the value of the dielectric constant only when the frequency is low. Under such conditions the body behaves almost the same as it would in the case of static fields. An excessive increase of frequency introduces other phenomena, which alter the value of the dielectric constant.

MICROSCOPIC CHARACTERISTICS OF POLARIZABILITY—Polarizability is a phenomenon originating from the various distributions of the charges in matter. The displacement of these charges can take place at three levels: subatomic, ionic, and molecular.

This illustration shows how these three levels are distinguished and how each of them contributes to dielectric phenomena, according to the frequency at which they are produced.

Illustration 2a represents an atom. It is shown on the left with its electron cloud in a wholly symmetrical form. This electron cloud, being negative, deforms, as shown on the right, when the atom is placed in an electrostatic field. The center of gravity of the positive and negative charges becomes displaced. The atom assumes the characteristic of a dipole, and the orientation of this dipole opposes the orientation of the inducing electric field.

Illustration 2b represents a crystal whose constituents are ions (and consequently carry charges). The ions of opposite sign are displaced in different directions when the crystal is placed in an electric field (as represented in the lower half of the illustration). A field of polarization is thus created inside the crystal.

Illustration 2c represents a solid in which the molecules have a permanent dipole moment. Under ordinary conditions (upper half) these molecules are oriented in such a way that their moments cancel each other and produce a zero resultant. When the same solid is subjected to the action of a magnetic field (lower half of the illustration), the dipoles become oriented and the solid is polarized.

The dielectric constant has a static definition and is related to the value of the index of refraction of electromagnetic radiations passing through the solid. The exact relationship should be $n^2 = \epsilon$ for molecules having no permanent dipole moment. In actual practice, however, the value of the dielectric constant is usually less than the square of the index of refraction. This discrepancy stems from the fact that the index of refraction is a magnitude that in turn depends on the speed with which the microscopic components move in the electric field. The speed with which an atom can deform (as in Illustration 2a) is enormously greater than the speed with which ions are displaced within a crystal (Illustration 2b); the displacement of ions is more rapid than the orientation of molecules described in Illustration 2c.

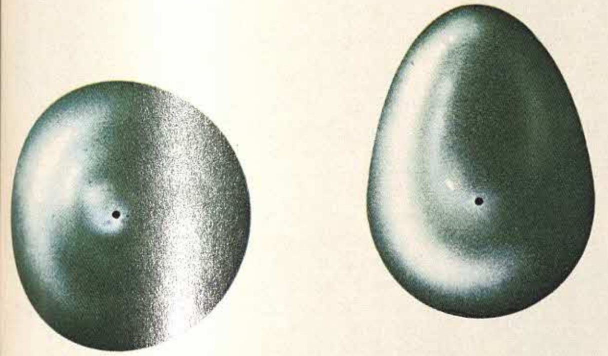
The graph (Illustration 2d) plots the total polarizability as the ordinate and the frequency as the abscissa. It can be seen from this graph that the polarizability diminishes as the frequency increases. The polarizability observed when the operation is performed under static conditions is the sum of the electronic, ionic, and molecular polarizabilities. The molecular polarizability gradually disappears as

Dielectrics are insulators–substances that are nonconductors of electricity. An understanding of their properties contributes to a better understanding of the structures of solids, just as the study of mechanical strength or thermal characteristics serves to explain those structures. In the case of dielectrics, these observations can be extended to include liquids and gases. Dielectric properties are derived from the atomic or molecular characteristics of a substance and are influenced by the structure of the solid or liquid in which they may be found.

the frequency increases, and only the atomic and ionic polarizability remain. This occurs in the range of the infrared (at least 10^{11} cycles per second and up to about 10^{14} cycles per second). In the range of visible light, the frequency of oscillation of the electromagnetic wave is so high that it prevents the ionic contribution. At the higher frequencies, therefore, only the atomic contribution is present. Comparison of the values of polarizability at the various frequencies reveals the intensity of the bonds between the molecular groups of a substance.

The analysis of molecular polarizability and the attempt to construct models of this phenomenon when it occurs in solids are useful inasmuch as the orientation of molecular groups in a complex crystalline structure depends on how the molecules are bound to one another to form the solid. The capacity of molecular groups in a solid to rotate depends on both the form of the molecule and the bonds that link it to surrounding molecules. The nearer the molecule comes to being spherical, the lower is its dipole moment—and the more readily it is able to rotate. The molecule of solid methane, CH_4, is an example of this; it has a nonpolar symmetry and can rotate freely.

2a



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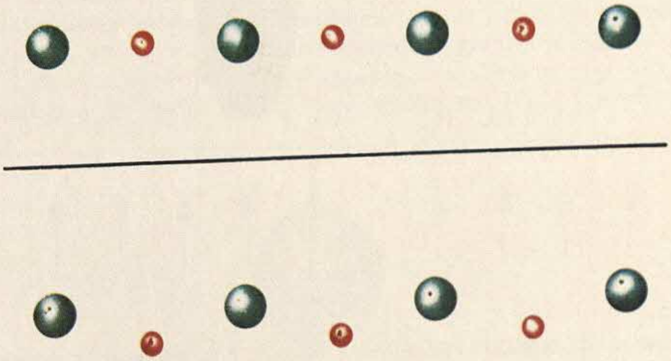

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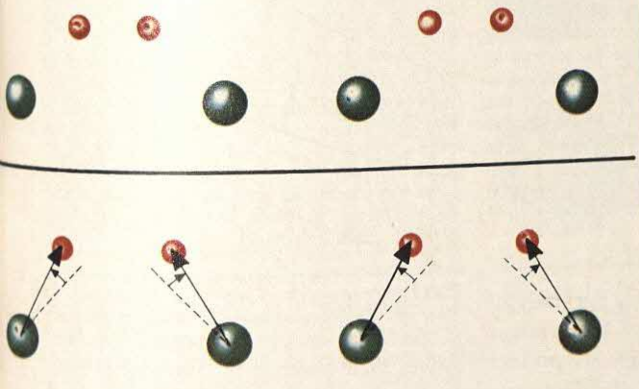

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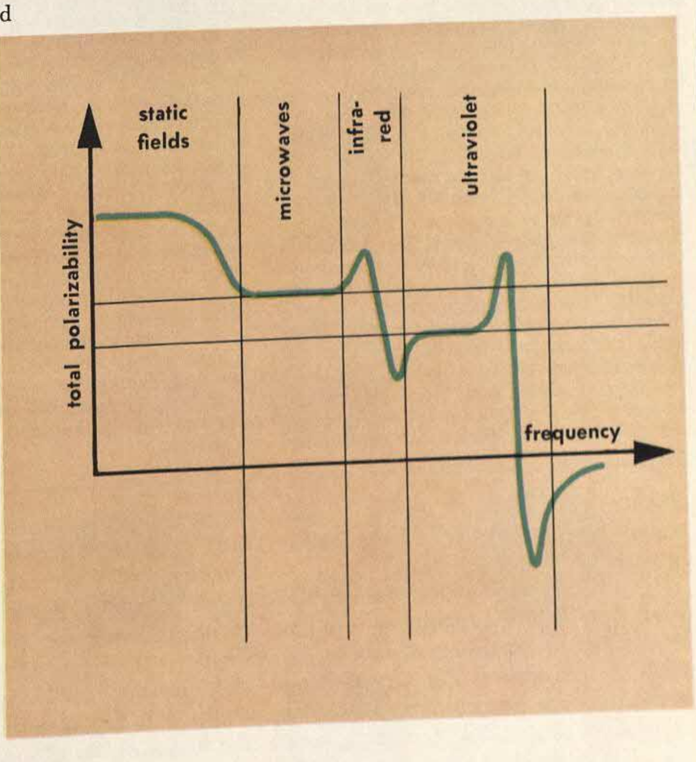

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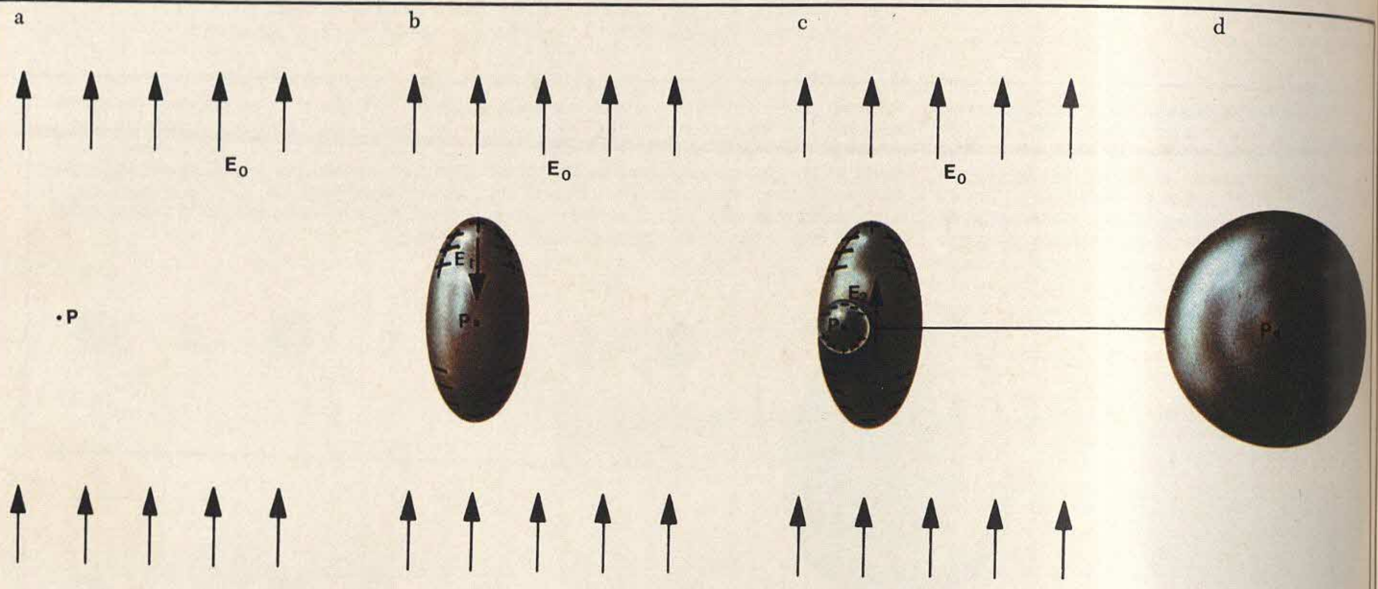


THE LOCAL ELECTRIC FIELD—These illustrations serve as aids to the understanding of the dielectric properties of solids. The arrows at the top and bottom represent the nature of the external electric field. This field should be considered as being produced by a pair of large, flat conductors, placed parallel and sufficiently far apart to ensure that the space between them is covered by a uniform field.

Illustration 3a represents the field in a vacuum. The value of the local field (**E_{local}**) at point **P** is equal to the value of the external field. If, however, point **P** is surrounded by a material body, the electric field is altered by the presence of this body. Physically, this alteration is due to the electric charges contained in the material substance, and these charges are themselves altered by the external field, moving from their normal equilibrium position. This displacement causes a variation in the external electric field; the charges within the material substance were in a certain equilibrium position before exposure to the external field, and their displacement creates a field that opposes the external field.

In reference to Illustration 3b, imagine point **P** as the center of an extremely small sphere, only large enough to contain a number of atoms of a simple crystal. Assume that this small sphere is at the center of such a simple crystal, formed as an ellipsoid as shown. The calculation of the effect of this solid body on an external electric field could be carried out by passing through the variation of position of each charge within the substance, but such a computation would be impossible because of the complexity of the structure. Instead, the calculation can be made in the manner illustrated, subtracting from the field **E_0** (the external field) a field **E_1**, caused by the matter—which can be initially approximated as that due to the charges on the external surface of the ellipsoid. The illustration shows that this effect is due to the gathering of the charge at the periphery of the ellipsoid; the presence of the charge sets up the field represented by the arrow pointing in the opposite direction to the arrows representing the external field. This new field, because of its opposition to the external field, is called the depolarization field, and weakens the resulting field experienced at point **P**.

The effect of the polarization of charges within the mass of the ellipsoid body also depends on the charge within the small sphere surrounding point **P**—the point at which the value of the field is sought. A formula developed by the Dutch physicist Hendrik Lorentz can be used to find the value of the field when the distribution of the charge on the internal surface of the sphere is known. The corresponding field (shown as **E_2** in Illustration 3c) is a vector parallel to the external field (**E_0**); it is represented in the illustration by an arrow parallel to the arrows representing the external field.

Illustration 3d shows the sphere surrounding point **P**, enlarged from its position within the ellipsoid. In cubic crystals—irrespective of whether they are simple, face-centered, or body-centered—calculations indicate that the field due to the atoms is zero. (The details of this calculation are complex and beyond the scope of the present discussion.) Substances more complex than crystals, of course, involve even more complex calculations, which are of such difficulty that few have been carried out beyond cubic structures.

Important properties of matter in general can be deduced from a basic knowledge of dielectric properties.

In a vacuum, an electrostatic field depends only on the intensity of the applied potential generating it and on the form of the surface (or space) over which these charges are distributed. The value of an electric field in matter, however, is influenced by other factors. Matter contains electric charges that are subject to the actions of attraction or repulsion, according to the sign of the charges. Such actions can displace the charges themselves or, if the charges are present in pairs, orient the dipoles. In either case, the displacement or orientation of the electric charges present in matter causes an alteration of the electric field in comparison with that same field in a vacuum. The extent of the alteration depends on the way and form in which the charges exist and are arranged within the matter.

The simplest way in which to visualize such an effect is to consider a substance subjected to an electric field of constant value. This is shown in the illustrations. If the same substance is placed in a rapidly varying electric field, the situation is more complex. In the latter case, matter reacts in different ways, according to the extent to which the charged elements are free to move under the action of the applied field. The accompanying illustrations relate dielectric characteristics to the structures of solids.

SEMICONDUCTORS

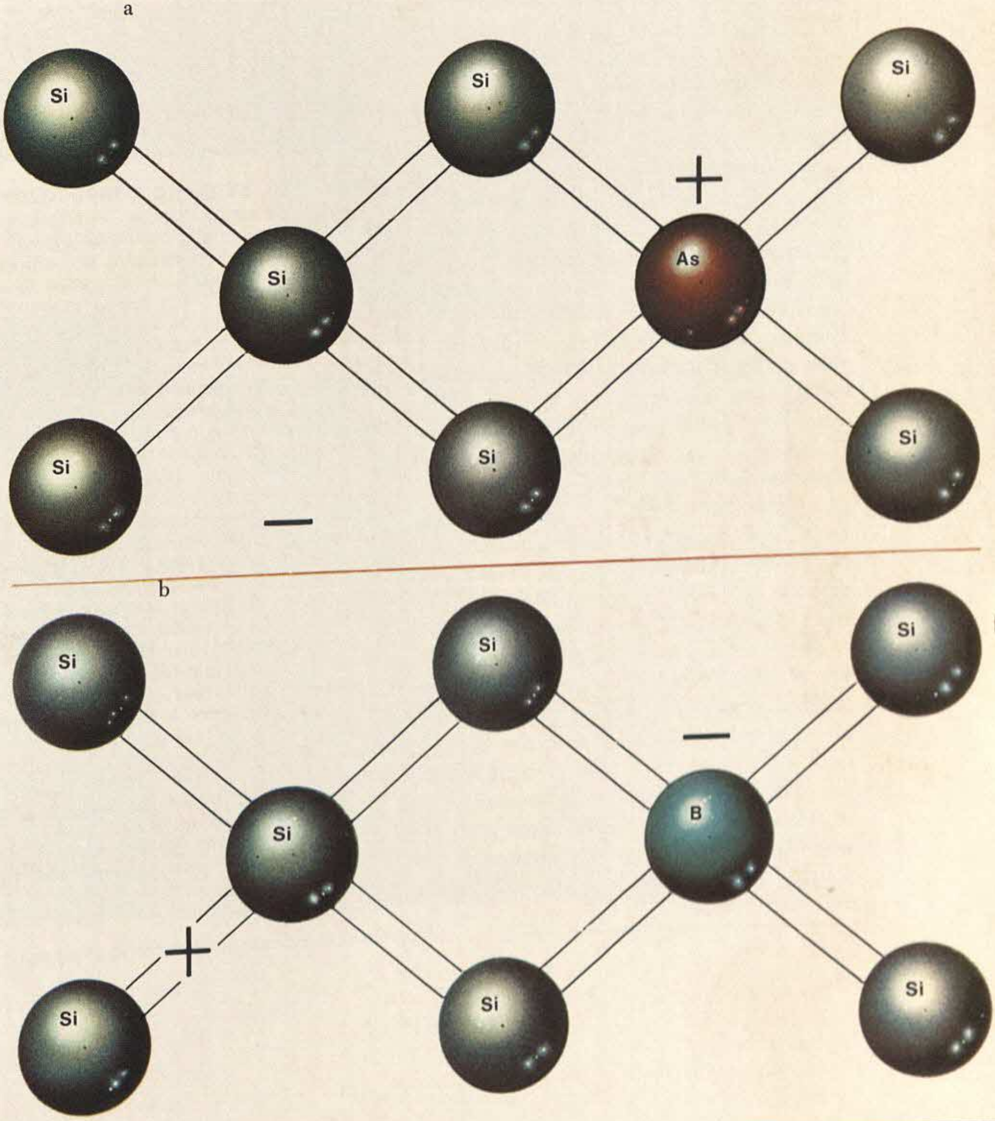
important substances used in electronics

Semiconductors, the materials from which transistors are made, are basic to electronic theory and systems. These substances, most familiarly germanium and silicon, react to temperature in a predetermined manner to conduct electrical energy.

Germanium was the first substance to be used as a semiconductor. It has now been almost completely superseded by silicon, which maintains its properties much better in the face of temperature variations. Many other semiconductor substances exist, but it is easier to interpret theory in the case of either germanium or silicon.

Conductivity in known substances is produced by the movement of ions, electrons, or the presence of crystalline defects. The value of this conductivity differs according to the particular substance, but is always referred to a specimen with a cross section of 1 cm^2 and a length of 1 cm. Measurements may be made on specimens of different dimensions, but the result is always related to a specimen of this size. Substances with a resistivity (the inverse of conductivity) of about 10^{-6} ohm/cm are said to be conductors; those whose resistivity lies between 10^{14} and 10^{22} ohm/cm are considered insulators.

Semiconductors, so called because of their intermediate position in the conductivity scale, have a resistivity between 10^{-2} and 10^{9} ohm/cm. While it is rela-



1

DONORS AND ACCEPTORS—The presence of impurities in germanium and silicon crystals can influence a semiconductor's conductivity. In Illustration 1a, the structure of these substances is shown in a single plane. At the center of each group of atoms in a crystal of pure silicon is another atom. If the crystal is polluted with a small percentage of arsenic, the central silicon atom will sometimes be displaced by an arsenic atom. Arsenic is pentavalent rather than tetravalent like silicon, and can lose an electron and become ionized. This free electron, added to the conduction band, further contributes to the conductivity of the crystal. For this reason, it is called a donor atom, and a semiconductor doped in this way is called an electron-rich, or N-type conductor.

Illustration 1b shows what happens when an element such as indium or boron is the source of the impurity. These elements are trivalent and thus will ionize by taking an atom from the crystalline structure. The presence of this acceptor atom is important in that it produces a hole that behaves like an electron (though less efficiently) and affects the conductivity. Semiconductors containing impurities of acceptor atoms are called P-type conductors.

The concentration levels of the impurities can be extremely low and still produce conductivity; for example, one part of boron in a hundred thousand is sufficient to increase the conductivity of silicon a thousand times. Impurities are not the only means of activitating perfect crystals. Some substances are good conductors because they have a stoichiometric excess of one component; cuprous oxide and zinc oxide are semiconductors of this type.

Donor or acceptor atoms alone do not turn a substance into a semiconductor. Their presence merely increases conductivity while conserving all other properties. Conductivity, then, depends on the probability that donor or acceptor atoms will ionize. It is relatively easy to calculate this probability for germanium or silicon, but quite difficult for other substances (for example, those with a stoichiometric deficiency). This is one reason why certain substances are being used as semiconductors; their properties have been revealed by actual experience instead of theory.

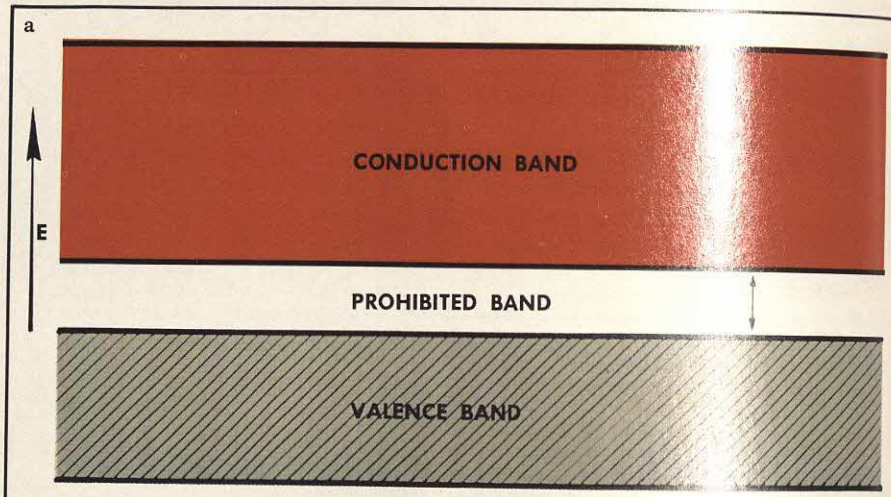
tively easy to study the properties of pure substances at either end of the scale (insulators or conductors), the properties of semiconductors may depend on different factors—temperature, thermal agitation, crystalline impurities, and lattice defects.

Thermal agitation can be determined to within a certain accuracy despite the difficulty of the required calculations. However, crystalline impurities and lattice defects require a great deal of experimentation in order to reach definite conclusions. For this reason, particular attention is being paid to the physics of semiconductors because of their great number of useful applications in electronics.

Semiconductor substances are most commonly used to make diodes and transistors. It is also possible to construct temperature-sensitive elements that react very rapidly and that can be accurately measured (thermistors). Other applications are in the manufacture of photodiodes and phototransistors (light-sensitive devices that are small in size and consume very little power); voltaic elements that emit a voltage when illuminated and that transform light energy into electricity (solar batteries); and devices that emit light radiation when stimulated electrically—devices having an efficiency greater than that of an ordinary light bulb and having almost unlimited life.

These various semiconductor products are of such considerable importance in modern science and technology that their invention was required before the large body of experiments aimed at establishing the properties of semiconductors could be performed. Among those products that have important applications are copper oxide, selenium, lead telluride, and lead sulfide.

2



INTRINSIC AND EXTRINSIC CONDUCTIVITY —Conduction in semiconductors is either intrinsic or extrinsic. Intrinsic conductivity results when a completely pure crystal is brought to absolute zero temperature. If the crystal conducts in this condition, it is due to structural reasons, or the mobility (in the widest sense) of the charges within the structure and the potentials that render these free and mobile. Extrinsic conductivity, conversely, depends on the presence of impurities; the nature and concentration of these impurities thus determine the value of conductivity.

Most semiconductors used today are intrinsic conductors to which some desired amount of extrinsic conductivity has been added. This effect is obtained by producing chemically pure monocrystals of the substance and adding a known amount of impurities.

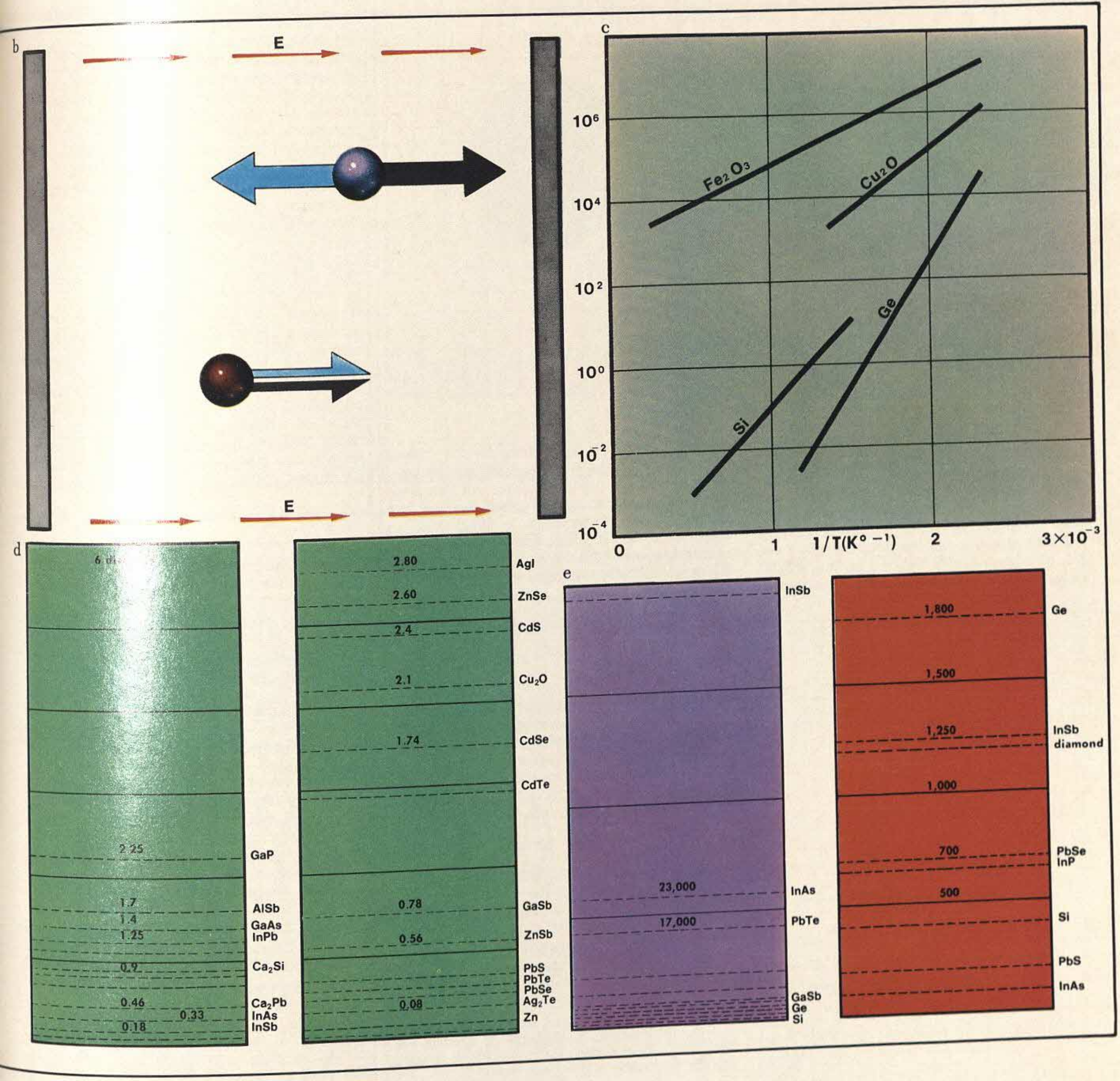
Illustration 2a represents the bands of energy that may be occupied by an electron within a semiconductor. The electron energies of a hydrogen atom display well-defined values that are separated by intervals of energy the electron cannot assume. In this illustration, however, the energies are arranged in wide bands. If the electrons are in the lower band, the crystal is only a weak conductor; but if they are increased (by raising the temperature, for example), the conductivity also increases, since some of the free electrons can now assume energies that correspond to the conduction band, and thus carry a charge.

Illustration 2b shows that the charges in a block of semiconductor material will become mobile when an electrostatic field **E** is applied; for example, the electrons (violet) move opposite to the direction of the field (these electrons are negatively charged), while the holes (red) move in the same direction as the field. The blue arrows represent the speed of the movement, and the black arrows the intensity of the resulting current.

Illustration 2c is an exponential graph, with the abscissa showing the inverse of the temperature in absolute units (1/T). For these semiconductors (the same law applies to all others), the variation is a straight line, experimentally determined, which means that the law of variation of the resistivity with temperature must be of the type exp $(-a/T)$. It can be seen that small temperature variations produce very considerable variations in the resistivity.

Illustration 2d shows the energy difference between the valence and conduction bands of many substances. This is one of the ways in which physicists determine whether or not a substance is a semiconductor. The most common semiconductors have an energy gap between bands on the order of 1 ev.

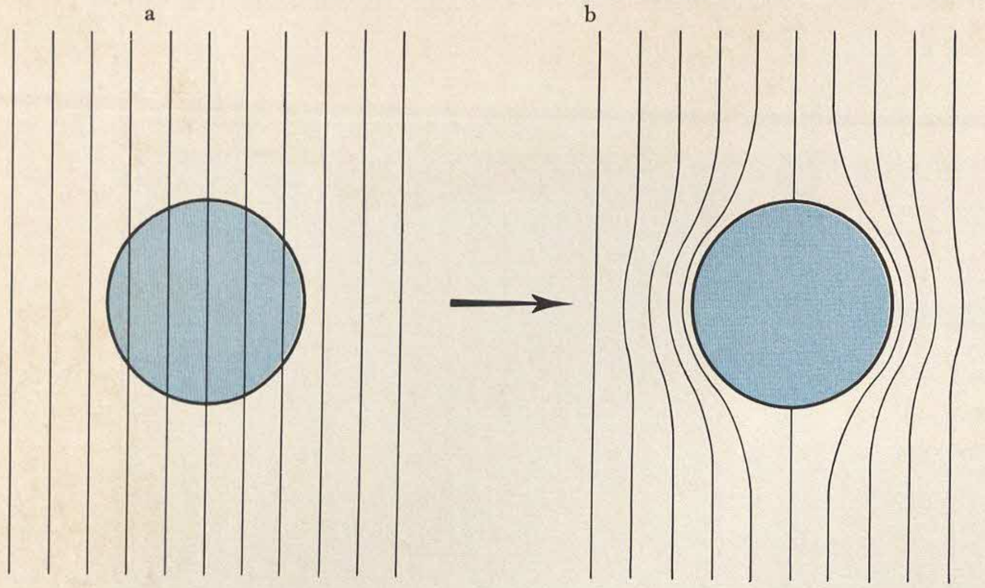
Illustration 2e indicates the important part played by the respective mobilities of electrons and holes in determining conductivity. The values of the mobilities of electrons and holes (at room temperature) are shown. Note that the mobility of the holes (red) is much less than that of the electrons (violet).


b
E
E
c
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
0
1
2
3×10^{-3}
$1/T(K^{\circ\,-1})$
Fe_2O_3
Cu_2O
Ge
Si
d
6 di
2.25
GaP
1.7
AlSb
1.4
GaAs
1.25
InPb
0.9
Ca_2Si
0.46
Ca_2Pb
0.33
InAs
0.18
InSb
2.80
AgI
2.60
ZnSe
2.4
CdS
2.1
Cu_2O
1.74
CdSe
CdTe
0.78
GaSb
0.56
ZnSb
PbS
PbTe
PbSe
Ag_2Te
0.08
Zn
e
InSb
23,000
InAs
17,000
PbTe
GaSb
Ge
Si
1,800
Ge
1,500
1,250
InSb
diamond
1,000
700
PbSe
InP
500
Si
PbS
InAs

SUPERCONDUCTIVITY

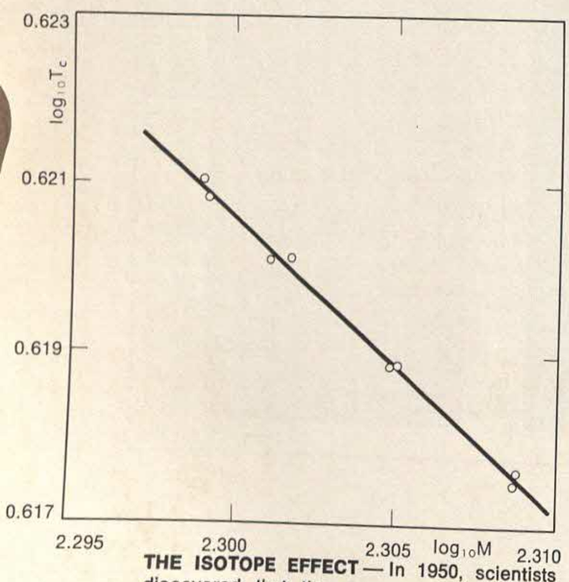
disappearance of electric resistance at low temperatures

1



THE MEISSNER EFFECT—An interesting characteristic of superconductivity is illustrated by an experiment carried out by W. Meissner and R. Ochsenfeld in 1933. They placed a wire of a conducting material in a magnetic field, arranged as shown in Illustration 1a. The induction lines of the field cross the section of the conductor as long as the wire remains a normal conductor. When the temperature of the wire is lowered below the critical value, however, the wire becomes a superconductor, and the induction lines of the magnetic field will no longer pass through the section. This phenomenon is diagramed in Illustration 1b. What this experiment shows is that the superconductive state is characterized by zero magnetic induction and that the conductor behaves like a perfectly diamagnetic material.

2



THE ISOTOPE EFFECT—In 1950, scientists discovered that the superconductive transitional temperature is not the same for the various isotopes of the same element and, therefore, that the transitional temperature of an element depends on its isotopic mass. The discovery was made through work with isotopes of mercury, which at that time could be isolated in sufficient quantities to permit experimentation for purposes of measuring the critical temperature. The graph shows that the relationship between the logarithm of the mass of the isotope and the logarithm of the transition temperature is represented by a straight line when plotted on a double logarithmic scale. This relationship may be expressed as

$$M^{1/2}T_c = \text{constant}$$

where M is the mass of the isotope and T_c is the critical temperature, the one at which the substance becomes a superconductor in the absence of a magnetic field. Two extreme values provide an idea of the range over which the critical temperature of mercury may vary: T_c varies from 4.185° K (−451.867° F) to 4.146° K (−451.937° F) as M varies from 199.5 to 203.4.

The aforementioned relationship permits the deduction of another relationship that is very simple and quite significant, namely

$$T_c/\theta = \text{constant}$$

where θ is the Debye temperature. This temperature, in fact, is proportional to the speed of sound in a crystal and this, in turn, is inversely proportional to the square root of the atomic mass of the isotope. The fact that the speed of sound is involved in this expression indicates that the interaction between the conducting electrons and the phonons of the lattice must be an important factor in the study of superconductivity.

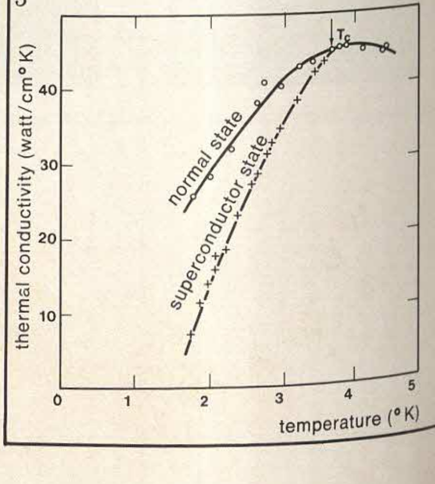
THE SUPERCONDUCTING ELEMENTS—This table is simply the periodic system of the elements presented in a manner to permit the identification of those elements that are superconductors and those that are not. The boxes containing the symbols of superconductor elements are colored blue, and all the other boxes are colored yellow; for each superconductor element, the value of the transition temperature (in °K) is given beneath the chemical symbol. Study of this table discloses some of the most salient characteristics concerning the distribution of superconductivity. Obviously, not all substances are superconductors; moreover, the distribution of the superconductor elements in the periodic table is not a random one. No alkali metals are superconductors, nor are any ferromagnetic metals, nor any antiferromagnetic metals.

The elements that are excellent metallic superconductors are not equally good conductors at ordinary temperatures. For example, at ordinary temperatures lead, tin, titanium, zirconium, and hafnium have resistivities that are on the order of 50 times the resistance of good metallic conductors, such as copper, gold, and silver. Most elements are not shown as superconductors, but this does not mean that these elements are not superconductors; to a great extent experiments with these substances have not been carried to the point where a conclusive answer can be given. In most cases, no experiments have been carried out below 0.07° K (−459.27° F), and it is, therefore, possible that some of the elements might become superconductors at temperatures below this point. An element can only be proved *not* to be a superconductor if the

THE SUPERCONDUCTIVITY OF COMPOUNDS—Superconductivity is a property of many substances that are alloys or intermetallic compounds rather than pure elements. Compounds of elements that individually are not superconductors can display the property of superconductivity; exceptional properties at times can be possessed by substances distributed in wires with a thickness of a few atomic layers or by substances distributed in a matrix in powder form. Apparently a perfect crystal structure is not necessary for a substance to become a superconductor, and yet at ordinary temperatures the crystal structure has a great deal of influence on conductivity.

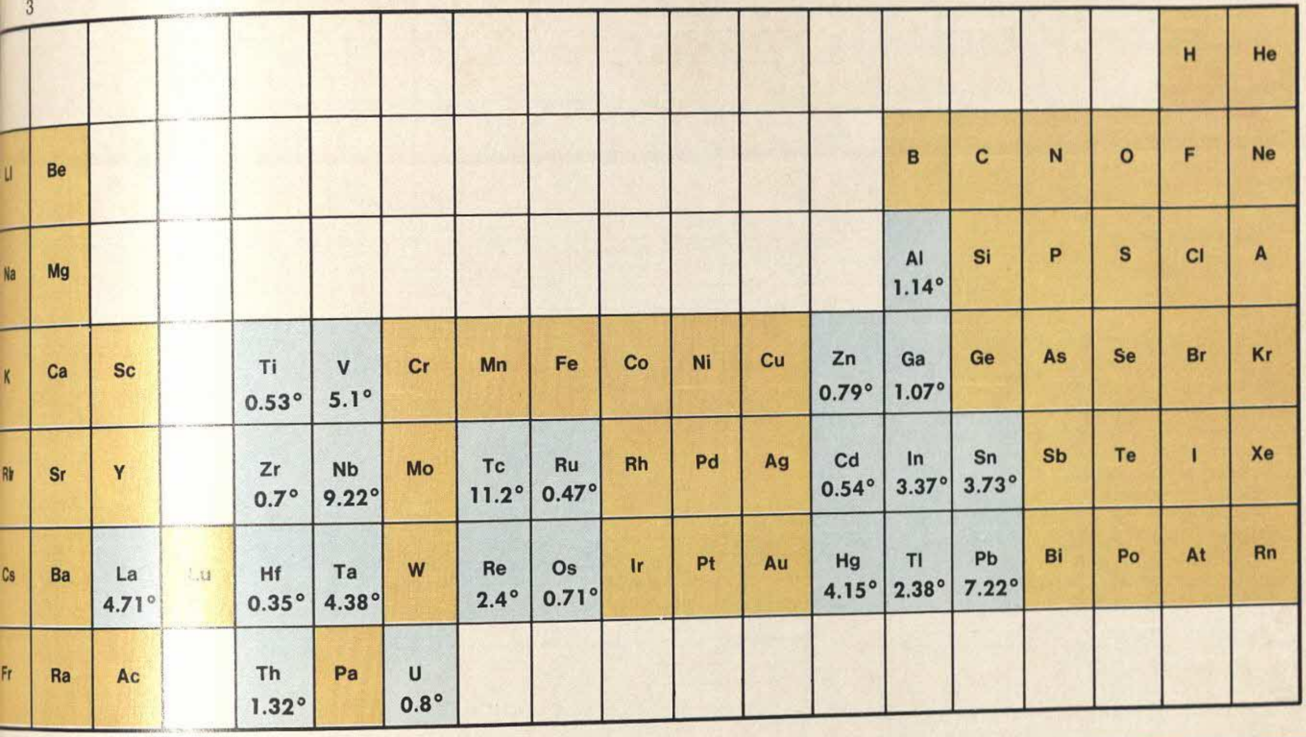
The temperature scale of the superconductor substances shown here does not highlight the fact that compounds generally have higher transition temperatures than pure elements.

5



experiments are carried out in the complete absence of any magnetic field, and the magnetic field of the Earth itself would be sufficient to prevent the observation of the phenomenon. However, even in the complete absence of any external magnetic field, the nuclear field could suffice to disturb the experiment and prevent the observation of superconductivity in the element.

3



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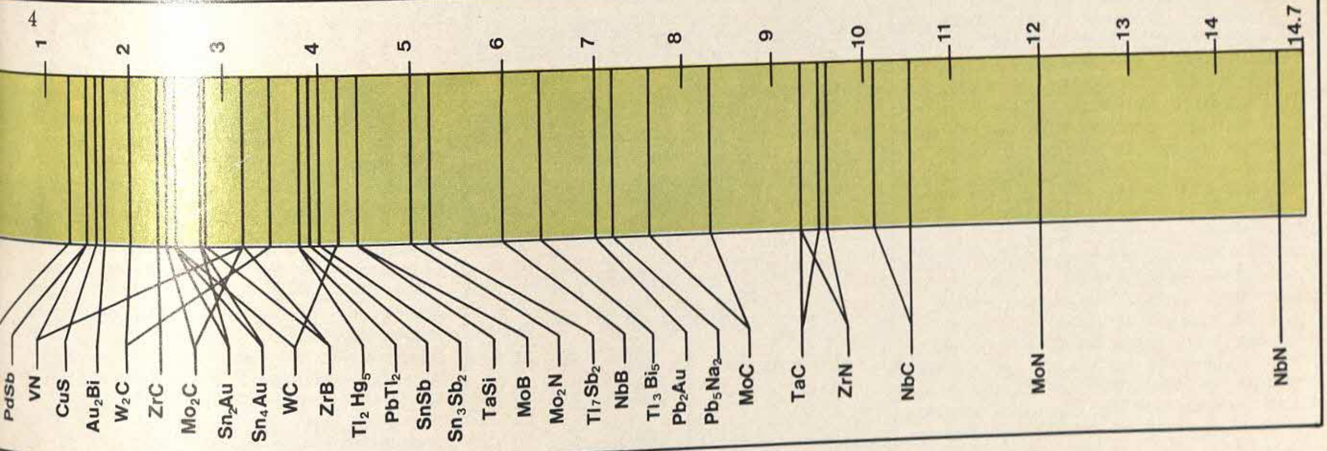


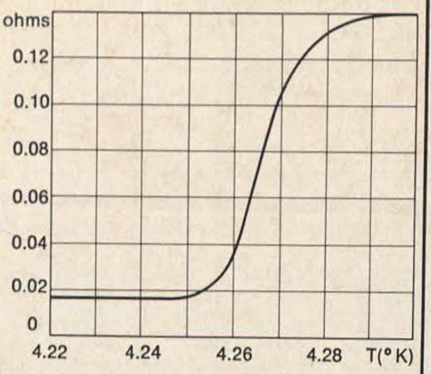
THE THERMAL CONDUCTIVITY OF SUPERCONDUCTORS—This graph presents the results of experiments carried out to determine the thermal conductivity of tin when it is changed into a superconductor. As usual, the experimental results were plotted first as points on the graph; and the points were subsequently connected to form the curves. The two curves indicate, respectively, the thermal conductivity of tin as a normal conductor and that of tin as a superconductor. They clearly show that the thermal conductivity of tin decreases when this substance becomes a superconductor. The experimental results suggest that the electrons of a superconductor are available for the transport of electric charge only—and not for the conduction of thermal energy. Consequently, they do not interact with the crystal to absorb and transfer vibration energy.

In 1911 a physicist by the name of H. Kamerlingh Onnes was working in the Low Temperature Research Laboratory at the University of Leiden, in The Netherlands. While studying the variations in the conductivity of solid mercury at extremely low temperatures, Onnes noticed that, at an absolute temperature of 4.2° (−451.8° F), the electrical resistivity of the metal had become zero or, at least, that it was no longer measurable. This discovery of superconductivity opened the way for some interesting studies concerning the structure of solids.

The first experiments to be conducted showed that the resistance of a metallic superconductor is really quite low. For example, if an electric current is made to flow through a ring made of a superconducting metal, the current will continue to flow even when there is no electromotive force at all.

Knowledge of the phenomenon of superconductivity has been extended greatly since its discovery. Nevertheless, the phenomenon is so complex that scientists have not yet been able to construct a theory that completely and satisfactorily explains it. This article is limited to a detailing of some experimental facts; the explanations that are offered are little more than phenomenological and intuitive.

6

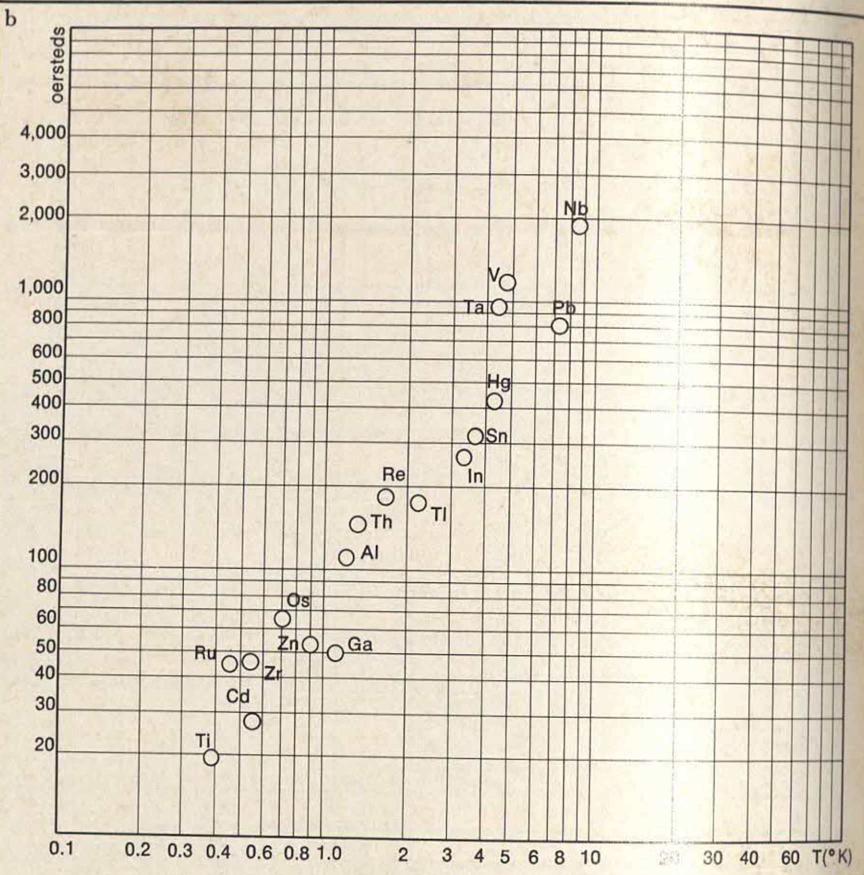


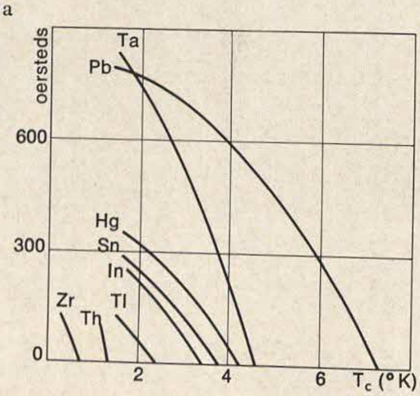
THE DISCOVERY OF SUPERCONDUCTIVITY—This graph constitutes a record of the measurements made by Kamerlingh Onnes during the experiment that led to the discovery of superconductivity. The temperatures to which the specimen of solid mercury was reduced are plotted as the abscissa, and the values of the electric resistance (in ohms) are shown by the ordinate. The graph shows that the resistance of the metal began to decrease at a temperature of about 4.29° K (−451.68° F) and that it practically reached zero at about 4.25° K. In other words, this decrease in resistivity occurred with a change of about a twenty-fifth of a degree of absolute temperature, about 0.04° K (0.07° F).

Scientists found that the ordinary methods of measuring resistance did not permit the establishment of the fact that the value of the resistance was effectively very low; therefore, another kind of experiment was devised, one in which electrons could be made to flow in a closed coil. At Leiden in 1948, a solenoid consisting of 700 m (2,296 ft) of lead wire was constructed and then turned into a superconductor through a lowering of the temperature. This solenoid was then subjected to an electromagnetic-induction phenomenon, which produced the current in it. In an ordinary solenoid, even one made of good conducting materials such as copper or silver, this current would have been dissipated almost instantaneously. In the 1948 Leiden experiment, on the other hand, the most sensitive measuring systems were incapable of detecting any appreciable variation in this current for at least 24 hours after its induction, although the intensity of the current should have decreased in an exponential manner. It was therefore possible to deduce that the resistance must have been at least 10^{17} times less than that exhibited by lead at ordinary temperatures; moreover, it must have been about 10^{15} times less than the resistance that lead could be expected to have at absolute zero if, ignoring the phenomenon of superconductivity, the values of the resistance that had been observed as the temperature of the lead was being lowered had been extrapolated.

In the course of a subsequent experiment a current of several hundred amperes was induced in another solenoid; once again, ordinary means of measurement were unable to detect any variation in the current during a period of one year. The results of this experiment suggest that the value of the resistance is at least a thousand times less than the value that had been deduced from the previous experiment.

7





THE EFFECT OF MAGNETIC FIELDS—In 1913, a short time after Kamerlingh Onnes discovered the phenomenon of superconductivity, the same scientist made another discovery. The phenomenon of superconductivity and the existence of conductors with zero resistance had led Onnes to deduce that very thin conductors could be made to carry currents of exceptional intensity. Nevertheless, the experiment set up to confirm this hypothesis failed completely, thereby showing that it was not possible to obtain currents of any desired intensity. A normal conducting wire can be changed into a superconductor by lowering its temperature below the critical value; however, if a very strong current passes through such a conductor, the superconductivity of the material is destroyed and the wire again acquires the properties of a normal conductor.

Three years after this experiment, in 1916, another physicist suggested that the phenomenon might be due to the magnetic field associated with the electron flow in the conductor. The graph in Illustration 7a shows that the magnetic field capable of destroying superconductivity depends on the temperature and that the field gradually changes as the temperature falls below the critical value—that is, the point at which the material becomes a superconductor. At the critical temperature, an infinitesimal field is sufficient to destroy the superconductivity of the material, but at lower temperatures, a strong field may be needed to obtain this result. The value of the field (in oersteds) has been plotted as the ordinate of the graph, and the temperature (in degrees absolute) is shown as the abscissa.

In the larger graph (Illustration 7b), the abscissa shows the transition temperature (that is, the temperature below which the material will become a superconductor if there is no magnetic field), and the ordinate indicates the value of the magnetic field that suffices to destroy the superconductivity of a material that has been cooled to absolute zero. Here all the elements capable of being made into superconductors lie on a straight line. At the top right-hand part of the graph are the "hard superconductors," so labeled because destruction of their superconductivity is very difficult; at the bottom left-hand part of the graph are the "soft superconductors," elements in which superconductivity can be destroyed by a weak field. The hardness of superconductors varies over a vast range of temperatures and values of the magnetic field.

THE ILLUSTRATED SCIENCE DICTIONARY

Particle to Potable Water

KEY TO PRONUNCIATION

The diacritical marks are:

ə	b*a*nan*a*, *a*but
ᵊ	preceding l, m, n as in batt*le*
ə̇	*e*lectric
ər	f*ur*ther
a	m*a*t
ā	d*ay*
ä	c*o*t, f*a*ther
au̇	n*ow*, *ou*t
e	b*e*t
ē	b*ea*t
i	t*i*p
ī	b*i*te
j	*j*ob, *g*em
ŋ	si*ng*
ō	b*o*ne
ȯ	s*aw*, *a*ll
ȯi	c*oi*n
th	*th*in
t̲h̲	*th*en
ü	r*u*le, f*oo*l
u̇	p*u*ll, w*oo*d
ue	German h*ü*bsch
u̅e̅	French r*ue*
yü	*u*nion
zh	vi*si*on

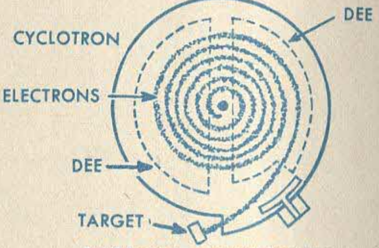
ˈ mark preceding the syllable with strongest stress.
ˌ mark preceding a syllable with secondary stress.

The system of indicating pronunciation in these volumes is used by permission from Webster's *Third New International Dictionary*, copyright 1961 by G. & C. Merriam Co., Publishers of the Merriam-Webster Dictionaries.

particle \'pärt-i-kəl\ *n.*

CHEMISTRY and PHYSICS. A very small piece of matter, usually smaller than can be seen in a microscope; technically, a piece of matter smaller than 250 millimicrons in diameter.

A subatomic PARTICLE *is smaller than an atom.*



PARTICLE ACCELERATOR

particle accelerator \'pärt-i-kəl ik-'sel-ə-ˌrāt-ər\

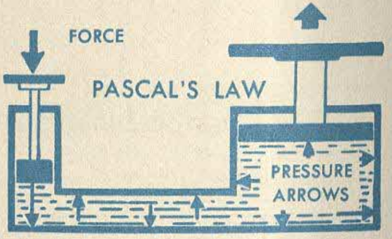
PHYSICS. A device that can give high speeds to bits of matter approximately the size of atoms and can direct them to a target; any one of several devices, such as the betatron, synchrotron or Van de Graaff generator.

The first artificial nuclear disintegration was achieved by using high-speed protons from a PARTICLE ACCELERATOR.

Pascal's law \pa-'skalz 'lȯ\

PHYSICS. A principle stating that pressure applied to an enclosed fluid is transmitted undiminished in all directions within the fluid and to the sides of its container.

The hydraulic lift is an application of PASCAL'S LAW.



passive immunity \'pas-iv im-'yü-nət-ē\

MEDICINE. Resistance to a specific disease, induced by one or more injections of antibodies that were previously formed in the blood of another person or animal; see *natural immunity.*

An injection of serum from the blood of horses or cattle previously immunized against tetanus toxins will give a human being an immediate PASSIVE IMMUNITY *to tetanus.*

pasteurization \ˌpas-chə-rə-'zā-shən\ *n.*

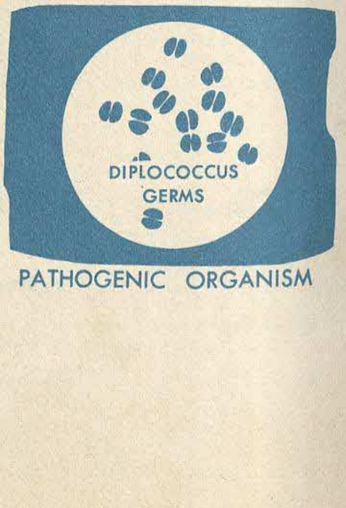
CHEMISTRY. A process of heating milk or other food products to a temperature of approximately 150° F. for about thirty minutes, followed by rapid cooling. The process kills or deactivates the bacteria that cause infectious diseases and delays souring or fermentation.

After PASTEURIZATION, *milk must be covered and kept cool in order to retain the effects of the process.*

pathogenic organism \ˌpath-ə-'jen-ik 'ȯr-gə-ˌniz-əm\

BIOLOGY and MEDICINE. A parasitic microorganism that will produce disease when established in a host.

The PATHOGENIC ORGANISM *diplococcus is a bacterium that causes lobar pneumonia.*



PATHOGENIC ORGANISM

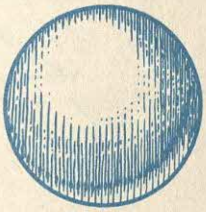
pathology \pə-'thäl-ə-jē\ *n.*

MEDICINE. The study of the nature of disease, especially the functional and structural changes in body tissues and organs that may cause, or be caused by, the disease.

Clinical PATHOLOGY *is concerned with the diagnosis of human diseases.*

pearl \'pər(-ə)l\ *n.*
ZOOLOGY. A hard, smooth, lustrous calcium carbonate structure found in such two-valved mollusks as oysters and clams. The structure is secreted by the mantle in concentric rings around parasites or other foreign bodies lodged between the mantle and shell.

A PEARL *of gem quality may be cultured by introducing a grain of sand between the mantle and shell of an oyster.*

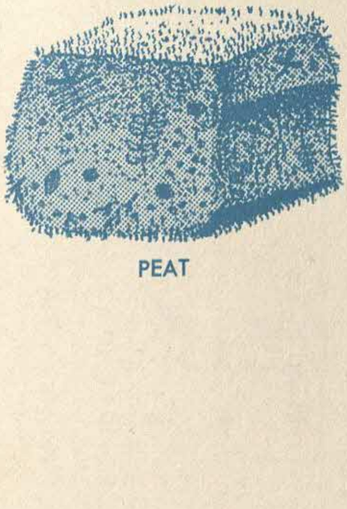

PEARL

peat \'pēt\ *n.*
BOTANY and EARTH SCIENCE. A dark-brown substance usually found in swampy areas and composed of partially-decayed and partially-disintegrated mosses, grasses, trees and other plant matter.

PEAT *is the first stage in the natural conversion of plant materials to coal.*

pebble \'peb-əl\ *n.*
EARTH SCIENCE. A small rock fragment from 2 to 64 mm. ($\frac{5}{32}$ to 2½ inches) in diameter.

A PEBBLE *is usually rounded by the abrasive action of running water.*


PEAT

pectin \'pek-tən\ *n.*
BOTANY and CHEMISTRY. One of a group of carbohydrates that occurs in such ripe fruits as apples, grapes and plums. Pectin dissolves in boiling water. After cooking with sugar solutions or fruit juices, it forms a gel when cooled.

PECTIN *is contained in the walls of some plant cells.*

pedalfer \pə-'dal-fər\ *n.*
EARTH SCIENCE. A major soil type characterized by an accumulation of iron oxides and clay in the layer (B-horizon) just under the topsoil.

PEDALFER *is found in the eastern half of the United States and most of Canada.*

pediatrics \ˌpēd-ē-'a-triks\ *n.*
MEDICINE. The branch of medicine that deals with the develop-

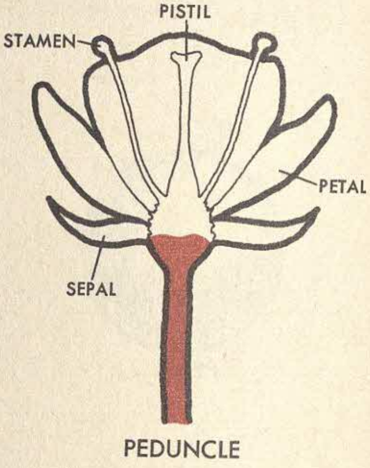
ment and hygienic care of children and with the prevention and treatment of children's diseases.

A physician who specializes in PEDIATRICS *is known as a pediatrician.*

pedicel \ˈped-ə-ˌsel\ *n.*

1. BOTANY. The stem of an individual flower in a flower cluster; also, the smallest branch of a peduncle. 2. ZOOLOGY. A short, stalklike part of an animal by which another, larger part is attached.

A PEDICEL *displays its flower away from the main stalk of a flower cluster.*



pedocal \ˈped-ə-ˌkal\ *n.*

EARTH SCIENCE. A major soil type characterized by calcium carbonate and a lesser amount of magnesium carbonate in the layer (B-horizon) just under the topsoil (A-horizon).

PEDOCAL *is found in the western half of the United States and in southern Alberta and Saskatchewan in Canada.*

peduncle \ˈpē-ˌdəŋ-kəl\ *n.*

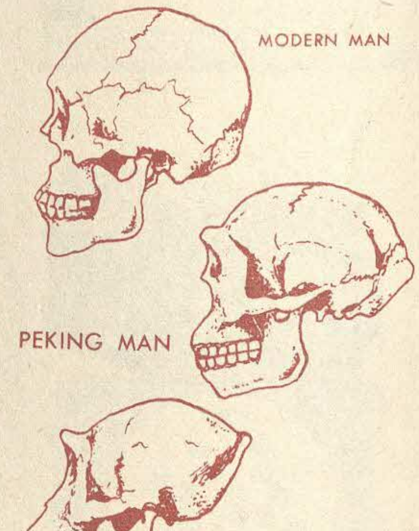
BOTANY. The main stalk of a flower cluster or of a single flower.

The enlarged or elongated end of the PEDUNCLE *is called the receptacle.*

pegmatite \ˈpeg-mə-ˌtīt\ *n.*

EARTH SCIENCE. A coarse-grained igneous rock occurring as a dike or large vein and composed principally of large feldspar and quartz crystals in granite. It may also contain mica, topaz and rare-earth minerals.

A single feldspar crystal over 40 feet in length has been found in a PEGMATITE.



Peking man \ˈpēkˈkiŋ ˈman\

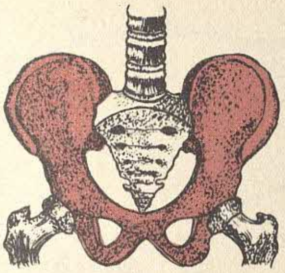
ZOOLOGY. A primitive form of man known from fossil remains found in a cave near Peking, China. It is believed that he lived about 500,000 years ago.

The brain of PEKING MAN *was smaller than that of present-day man.*

pelagic \pə-ˈlaj-ik\ *adj.*

BIOLOGY and EARTH SCIENCE. A zone or layer of water that is independent of both the bottom and the shore.

Waters in the PELAGIC *zone of the sea are classified on the basis of available light, the euphotic being the lighted zone and the aphotic the unlighted.*

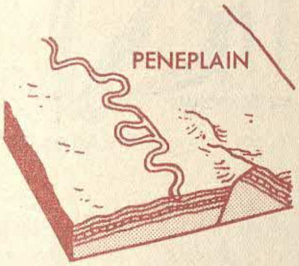


PELVIS

pelvis \'pel-vəs\ *n.*

ANATOMY and ZOOLOGY. A basin-shaped ring of bones that forms the supporting floor of the abdominal cavity; also, any basinlike cavity within an organ, as within the kidney.

The PELVIS *of a male human being is usually smaller in proportion to the rest of his body than is the pelvis of a female.*



peneplain \'pēn-i-ˌplān\ *n.*

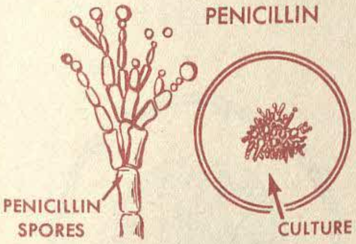
EARTH SCIENCE. An extensive, nearly-level surface that has been formed by erosion.

PENEPLAIN *is used only in referring to a very large area.*

penicillin \ˌpen-ə-'sil-ən\ *n.*

MEDICINE. An antibiotic substance obtained from cultures of a mold, *Penicillium notatum*, and used effectively in the treatment of a number of diseases and infections. Penicillin was the first of a group of compounds known as miracle drugs.

PENICILLIN *is especially effective in the treatment of infections caused by some strains of coccus bacteria.*



peninsula \pə-'nin(t)-sə-lə\ *n.*

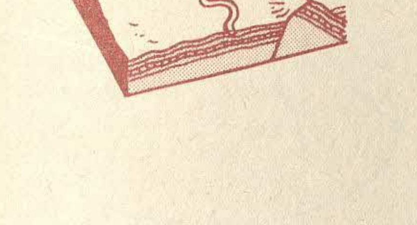
EARTH SCIENCE. A piece of land projecting out into the water from the mainland. It is almost surrounded by water and connected by a narrow strip to the mainland.

A PENINSULA *is land that, because of its location or composition, has not been destroyed by wave action.*

pentagon \'pent-i-ˌgän\ *n.*

MATHEMATICS. A closed plane figure, or polygon, that has five sides.

The sum of the interior angles of a PENTAGON *is 540 degrees.*



penumbra \pə-'nəm-brə\ *n.*

ASTRONOMY and PHYSICS. A region of partial illumination that surrounds the dark inner shadow, or umbra, of an intervening body; also, the shaded region around the darker, inner part of a sunspot.

Penumbral lunar eclipses occur when the moon passes through the PENUMBRA *of the earth's shadow and result in weakened moonlight.*

peptic \'pep-tik\ *adj.*

PHYSIOLOGY. Referring to digestion or the digestive enzyme pepsin.

PEPTIC *processes are inhibited by exercise.*

peptone \'pep-ˌtōn\ *n.*

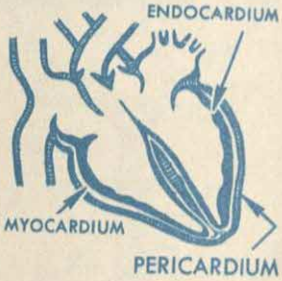
CHEMISTRY and PHYSIOLOGY. One of the complex, soluble substances formed by the digestive action of enzymes on protein. A peptone is formed by the partial hydrolysis of protein and is one step removed from the final product, a mixture of amino acids.

A PEPTONE *undergoes further digestion by pancreatic and intestinal juices.*

percent \pər-'sent\ *n.*

MATHEMATICS. Hundredth, or by the hundred; denoted by the symbol %.

To find 6 PERCENT *of a quantity, multiply the quantity by 6/100, or .06.*



percolate \'pər-kə-ˌlāt\ *v.*

CHEMISTRY. To circulate a liquid through fragments or pores of a solid mixture. In the process, the liquid extracts soluble substances from the mixture.

Coffee is often prepared by causing hot water to PERCOLATE *through ground coffee beans.*

percolation bed \ˌpər-kə-'lā-shən 'bed\

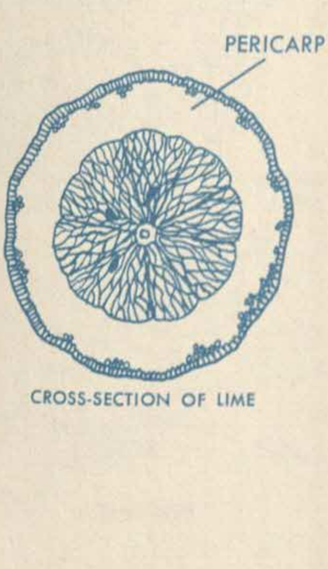
CHEMISTRY and ENGINEERING. Layers of porous or granular material through which a liquid is passed as a means of trapping and removing some impurities.

One method of purifying water is allowing it to trickle slowly through a PERCOLATION BED *of sand, gravel or charcoal.*

perennial \pə-'ren-ē-əl\ *adj.*

BOTANY. Referring to a plant that persists in whole or part throughout the year and that lives from year to year; also see *annual* and *biennial.*

The roots of the PERENNIAL *oriental poppy survive the winter in temperate zones.*



CROSS-SECTION OF LIME

pericardium \ˌper-ə-'kärd-ē-əm\ *n.*

ANATOMY and ZOOLOGY. A double-layered, saclike membrane that surrounds the heart and is attached to the central tendon of the diaphragm.

The heart functions in a fluid medium that is contained by the PERICARDIUM.

pericarp \'per-ə-ˌkärp\ *n.*

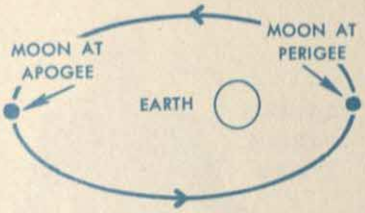
BOTANY. An enlarged, mature ovary that encloses seeds.

Hairlike growths from the PERICARP *form the fleshy part of a lime.*

pericycle \'per-ə-ˌsī-kəl\ *n.*

BOTANY. A layer of thin-walled cells that occurs between the cylinder of conductive tissues and the endodermis in stems and roots.

By cell division, the PERICYCLE *gives rise to the tissues that produce lateral roots.*



PERIGEE

perigee \'per-ə-(ˌ)jē\ *n.*

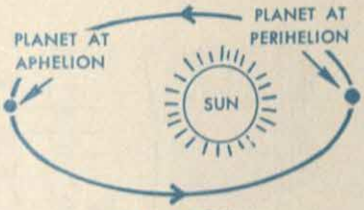
ASTRONAUTICS and ASTRONOMY. The point nearest the earth in the path, or orbit, of the moon or of an artificial satellite; opposite of apogee.

At PERIGEE, *the moon is about 221,500 miles from the earth.*

perihelion \ˌper-ə-'hel-yən\ *n.*

ASTRONOMY. The point that is nearest the sun on the orbit taken by a planet, comet or other celestial body as it travels around the sun; opposite of aphelion.

In early January, the earth is at PERIHELION.



PERIHELION

perimeter \pə-'rim-ət-ər\ *n.*

MATHEMATICS. The sum of the lengths of the sides of a polygon; also, the length of, or the distance around, a closed curve.

The PERIMETER, *or circumference, of a circle equals its radius times 2 π (pi).*

period \'pir-ē-əd\ *n.*

1. EARTH SCIENCE. A division of geological time, longer than an epoch and shorter than an era, that is characterized by the formation of certain rock strata or fossils in a definite sequence. 2. ASTRONOMY. The time it takes a planet, satellite, star or other body to revolve around another astronomical body. 3. PHYSICS. The time it takes a series of events, or a cycle, to start, happen and begin to repeat itself.

Many coal beds were formed during the Pennsylvanian PERIOD *of the Paleozoic era.*

PERIOD
(PENNSYLVANIAN)

periodic law \ˌpir-ē-'äd-ik 'lȯ\

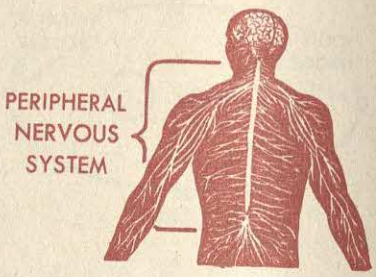
CHEMISTRY. The chemical law stating that the properties of chemical elements vary periodically when the elements are arranged in order of increasing atomic numbers.

By the use of the PERIODIC LAW, *the properties of a family of elements can be learned from the known properties of one element of the family.*

periodic table \\ˌpir-ē-ˈäd-ik ˈtā-bəl\\

CHEMISTRY. A systematic arrangement of the chemical elements into periods and groups. The elements are divided into periods on the horizontal rows and into groups in the vertical columns, arranged so that elements are in order of increasing atomic numbers. The elements in a given vertical column have similar properties; see periodic table, page 620.

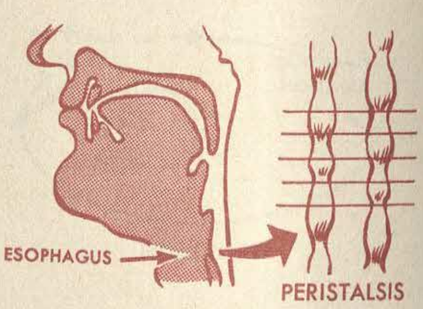
The main value of the PERIODIC TABLE *is its organization of the elements into a logical and understandable pattern that makes study of the elements easier.*



peripheral nervous system \\pə-ˈrif-(ə-)rəl ˈnər-vəs ˈsis-təm\\

ANATOMY and ZOOLOGY. All of the nerves outside the brain and spinal cord (central nervous system); in man, the 12 pairs and one single cranial nerve, the 31 pairs of spinal nerves and the nerves and ganglia of the autonomic nervous system.

The nerves of the PERIPHERAL NERVOUS SYSTEM *branch to all parts of the body and carry impulses both toward and away from the central nervous system.*



peristalsis \\ˌper-ə-ˈstȯl-səs\\ *n.*

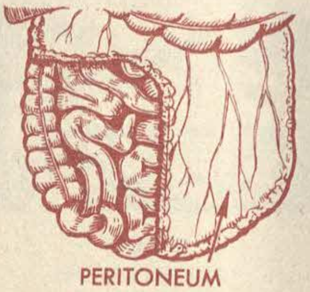
PHYSIOLOGY. The wavelike muscle contractions in the walls of various hollow organs of the body, as in the esophagus during swallowing.

Ringlike muscles and lengthwise muscles contract alternately during PERISTALSIS.

peritoneum \\ˌper-ət-ᵊn-ˈē-əm\\ *n.*

ANATOMY and ZOOLOGY. A thin membrane that lines the abdominal cavity and covers the soft organs in the body. It is made up of cells that produce a colorless, serous, or watery, fluid.

The mesentery is a double layer of PERITONEUM *that supports the small intestine.*



permafrost \\ˈpər-mə-ˌfrȯst\\ *n.*

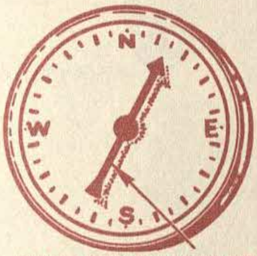
EARTH SCIENCE. A layer of ground a few inches below the surface that remains frozen the year around. It occurs at high altitudes and in polar regions.

Highway construction in Alaska and northern Canada is difficult because PERMAFROST *hinders excavation in these regions.*

permanent hardness \\ˈpərm-(ə-)nənt ˈhärd-nəs\\

CHEMISTRY. A condition of water resulting from dissolved calcium and magnesium compounds that cannot be removed from solution by boiling and that cause the water to require large amounts of soap to form suds. Such water may be softened by adding washing soda or borax.

Mineral ions that cause PERMANENT HARDNESS *are removed from water by an ion-exchange process in home water-softening units.*



PERMANENT MAGNET

permanent magnet \'pərm-(ə-)nənt 'mag-nət\
PHYSICS. A magnet that keeps its magnetic properties after the original magnetizing force is taken away.

Alnico, an alloy of iron, nickel, aluminum and cobalt, makes a good PERMANENT MAGNET.

permanganate \(ˌ)pər-'maŋ-gə-ˌnāt\ *n.*
CHEMISTRY. Any one of a group of compounds that contain the permanganate ion $M_nO_4^-$. The most common is potassium permanganate that, in solution, is sometimes used as a disinfectant.

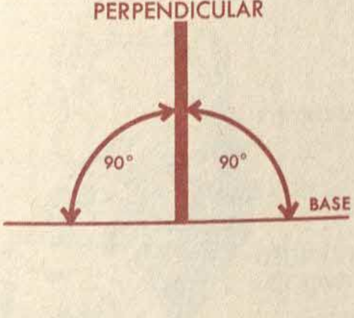
A PERMANGANATE, *like the salts of all peracids, is a good oxidizing agent.*

permeability \ˌpər-mē-ə-'bil-ət-ē\ *n.*
PHYSICS. The property of a substance that allows it to conduct or absorb magnetic lines of force; also, the property of a solid that permits fluid molecules or dissolved substances to diffuse into and through it.

The magnetic PERMEABILITY *of iron is greater than that of air.*

permutation \ˌpər-myü-'tā-shən\ *n.*
MATHEMATICS. An arrangement of a given set of elements in a specific order; a one-one transformation, or mapping, of a finite set into itself.

One PERMUTATION *of the set of letters a, b and c is acb, while other possible permutations are abc, bac, bca, cab and cba.*



peroxide \pə-'räk-ˌsīd\ *n.*
CHEMISTRY. A compound in which there is a high proportion of oxygen.

A PEROXIDE *commonly used as a bleaching agent is hydrogen peroxide,* H_2O_2.

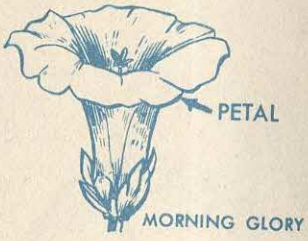
perpendicular \ˌpər-pən-'dik-yə-lər\ *n.*
MATHEMATICS. A straight line or plane that intersects another line or plane so that adjacent right angles are formed at the intersection.

A PERPENDICULAR *drawn from a vertex of an acute triangle to the opposite side creates two right triangles.*

perpetual motion \pər-'pech-(ə-)wəl 'mō-shən\

PHYSICS. In theory, constant motion that continues indefinitely and that involves no transfer of energy. Such motion can occur only when an object moves in a frictionless medium and no external forces act on it.

All of man's efforts to produce PERPETUAL MOTION *have failed.*



perturbation \ˌpərt-ər-'bā-shən\ *n.*

1. ASTRONOMY. The variation between the computed orbit of a celestial body and its observed orbit, caused by gravitational forces of other bodies on the celestial body. 2. PHYSICS. The departure of a particle from its predicted path, due to some cause other than collision.

The PERTURBATION *of Neptune from its computed orbit led to the discovery of Pluto.*

petal \'pet-ᵊl\ *n.*

BOTANY. One unit of the inner floral envelope of a flower. A petal is often leaflike and colored.

The scent, structure and color of a PETAL *may be adaptations that attract pollinating insects and birds.*

petiole \'pet-ē-ˌōl\ *n.*

1. BOTANY. The stalk that joins a leaf to a stem. 2. ZOOLOGY. A stalklike part.

A honey locust leaflet does not have a PETIOLE.

petrifaction \ˌpe-trə-'fak-shən\ *n.*

EARTH SCIENCE. The process by which the remains of plants or animals are changed into stone or a stonelike substance and by which they are preserved as fossils. The change is a chemical reaction.

Silica and calcium carbonate are two common substances involved in PETRIFACTION.

petrified wood \'pe-trə-ˌfīd 'wu̇d \

EARTH SCIENCE. Wood that has been infiltrated by silica, which has replaced the woody material cell by cell. Petrified wood is usually found in the form of fallen logs, tree trunks and stumps.

The microscopic structure of cells is preserved and can be identified in PETRIFIED WOOD.

petroleum \pə-'trō-lē-əm\ *n.*

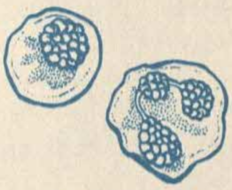
CHEMISTRY and EARTH SCIENCE. A naturally-occurring oily liquid that ranges in color from light amber to black and that is the crude oil or raw material used in the production of gasoline, kerosene, paraffin and asphalt; also, a mixture composed principally of many different hydrocarbon compounds.

Many geologists believe that PETROLEUM *is formed by some underground or underwater process that accompanies the decomposition of dead plant and animal matter.*

petrology \pə-'träl-ə-jē\ *n.*

EARTH SCIENCE and ENGINEERING. The study of rocks; the science of rock origin, structure, composition and alterations. Petrology also includes the study of ore and mineral deposits.

Mining and civil engineers, geologists and agronomists are among those who need a knowledge of PETROLOGY.



PHAGOCYTE

***p*H**

A symbol pertaining to the *p*H scale. See *p*H *scale.*

phagocyte \'fag-ə-ˌsīt\ *n.*

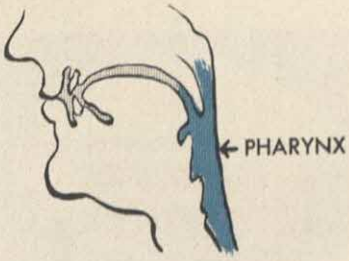
MEDICINE, PHYSIOLOGY and ZOOLOGY. Any body cell that ingests by engulfing foreign bodies for food, is amoeboid in action and is capable of moving through tissue; in vertebrates, a blood corpuscle that feeds on bacteria; in man, certain white blood corpuscles that ingest microorganisms, cell fragments and foreign particles within body tissues.

A PHAGOCYTE *leaves the bloodstream and enters infected tissue where it ingests, or devours, the organisms causing the infection.*

pharmacology \ˌfär-mə-'käl-ə-jē\ *n.*

MEDICINE. The science that includes the study of drugs and chemicals and their effects on man and animals.

Standardization of vitamin capsule purity and content is a typical concern of PHARMACOLOGY.



pharynx \'far-iŋ(k)s\ *n.*

ANATOMY and ZOOLOGY. A saclike part of the digestive tract in animals, located at the back of, or behind, the mouth.

In man, the PHARYNX *is continuous with the esophagus below it.*

phase \'fāz\ *n.*

1. ASTRONOMY. Any one of the changing and recurring stages of the apparent illumination of the moon or planets. 2. BIOLOGY. Any one of the five stages of mitosis in the development of a plant or animal cell. 3. ZOOLOGY. Any one of several skin or body-cover variants, especially among amphibians. 4. CHEMISTRY. A state of matter, such as a solid, liquid or gas; also, in a

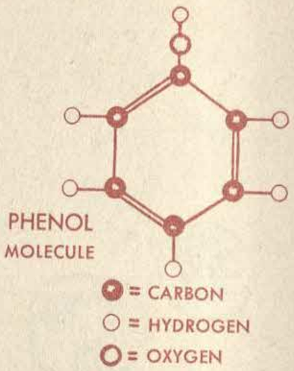
mixture, a solid, liquid or gas that has boundaries between it and other parts of the mixture. 5. PHYSICS. A particular point, place or stage in a series of events.

From first quarter to full and from full to third quarter, the moon is in the gibbous PHASE.

phenol \\'fē-ˌnōl\\ *n.*

CHEMISTRY. C_6H_5OH. A soluble, crystalline compound, produced from coal tar and used as a starting compound in the manufacture of many dyes, plastics and explosives. It is a powerful caustic poison; also called carbolic acid.

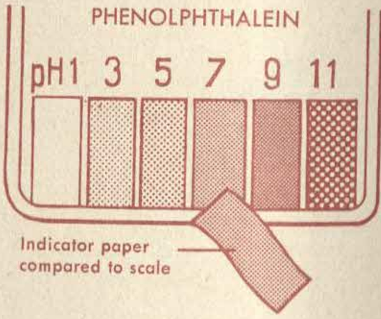
Although PHENOL *is corrosive to the skin, a dilute solution in water is sometimes used as a disinfectant.*



phenolphthalein \\ˌfē-ˌnōl-'thal-ē-ən\\ *n.*

CHEMISTRY. A chemical compound frequently used to indicate whether a solution is acid or alkaline. It turns red under alkaline conditions and is colorless under acid conditions.

PHENOLPHTHALEIN *turns red in a solution of* pH *9 or higher and is colorless in a solution of less than* pH *9.*



IN INDICATOR PAPER CAUSES COLOR CHANGE WHEN ALKALINITY LEVEL OF A SOLUTION IS BETWEEN 8.3 and 10.0

phenomenon \\fi-'näm-ə-ˌnän\\ *n.*

A fact or occurrence that may be described and explained on a scientific basis; sometimes, an unusual or rare fact or occurrence.

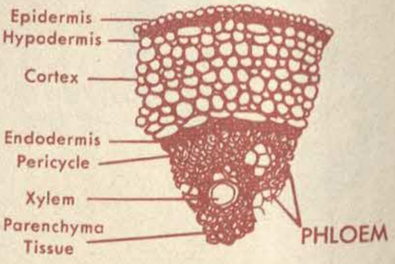
The aurora borealis is a PHENOMENON *caused by electrical disturbances in the atmosphere.*

phenotype \\'fē-nə-ˌtīp\\ *n.*

BIOLOGY. The physical appearance of an organism, resulting from its genetic makeup; see *genotype.*

A dark-eye PHENOTYPE *may have a hybrid (Bb) or pure (BB) genotype.*

CROSS SECTION OF SMILAX ROOT



phloem \\'flō-ˌem\\ *n.*

BOTANY. Food-conducting tubular tissue, and associated tissues, in seed plants and ferns, which transports organic nutrients both up and down; see *xylem.*

Maple syrup is made from sap taken from the PHLOEM *of sugar maples.*

phosphate \\'fas-ˌfāt\\ *n.*

CHEMISTRY. Any one of a number of compounds formed from phosphoric acid, H_3PO_4, by replacing one, two or three of its hydrogen atoms with metallic ions. Some of these compounds are used as cleansing agents, fertilizers or as water softeners.

Adenosine triphosphate (ATP) is a PHOSPHATE *having an important function in producing energy for muscular action in animals.*

phosphor \'fȧs-fər\ *n.*

CHEMISTRY and PHYSICS. Any substance that gives off light when energized by the absorption of some form of energy, such as electricity or chemical energy.

Luciferin, the PHOSPHOR *in the abdomen of fireflies, gives off light when it is energized by certain biochemical reactions.*

PHOSPHOR

phosphorescence \ˌfȧs-fə-'res-ᵊn(t)s\ *n.*

CHEMISTRY and PHYSICS. An emission of light from a substance after the energy source that stimulated the light emission is removed.

Zinc sulfide may display PHOSPHORESCENCE *for as long as ten hours after being energized by sunlight.*

phosphorus \'fȧs-f(ə-)rəs\ *n.*

CHEMISTRY. A solid, nonmetallic element that is too active chemically to be found uncombined in nature, and that occurs in five different forms (allotropes). Symbol, P; atomic number, 15; atomic weight, 30.9738.

The yellow allotrope of PHOSPHORUS, *a waxy solid, oxidizes readily in air, but the red allotrope, a noncrystalline powder, does not.*

phot \'fōt\ *n.*

PHYSICS. A unit of illumination equal to one lumen per square centimeter.

A PHOT *may be used for measuring the light emitted by a television picture tube.*

PHOSPHORESCENCE

photochemistry \ˌfōt-ō-'kem-ə-strē\ *n.*

CHEMISTRY and PHYSICS. A branch of science that deals with chemical reactions that are caused, or started, by light.

Scientists working in PHOTOCHEMISTRY *concentrate much effort toward understanding photosynthesis.*

photoconductivity \ˌfōt-ō-ˌkän-ˌdək-'tiv-ət-ē\ *n.*

PHYSICS. An increase in the electrical conductivity that certain solids, usually crystals, show when they absorb light.

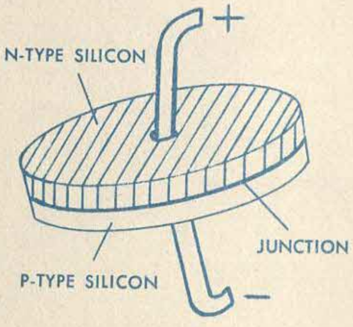
Selenium, germanium and lead sulfide are three substances that show PHOTOCONDUCTIVITY.

photoelectric cell \ˌfōt-ə-wə-'lek-trik 'sel\
ENGINEERING and PHYSICS. An electronic device that produces an electric current only when light strikes it. A photoelectric cell utilizes a metal, such as potassium, that gives off electrons in proportion to the intensity of light rays falling upon it; also called electric eye.

A PHOTOELECTRIC CELL *can be connected to a telescope in such a way that it measures changes in the brightness of a distant star.*

photoelectric effect \ˌfōt-ə-wə-'lek-trik i-'fekt\
PHYSICS. The action by which certain substances give off free electrons as a result of absorbing light energy. The effect is typical of such metals as cesium and sodium.

The electric eye makes use of the PHOTOELECTRIC EFFECT.



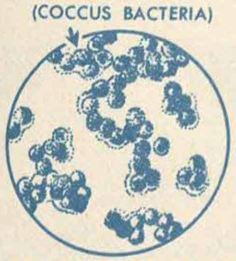
PHOTOELECTRIC CELL

photometry \fō-'täm-ə-trē\ *n.*
PHYSICS. The scientific study of light measurement. It is concerned with the intensity, output, illumination, distribution, reflection and colors of light.

In PHOTOMETRY, *a device called a photometer is frequently used to make measurements of light intensity.*

photomicrograph \ˌfōt-ə-'mī-krə-ˌgraf\ *n.*
PHYSICS. A picture taken of a microscopic object through a microscope.

A PHOTOMICROGRAPH *of bacteria is a convenient reference in the study of bacteriology.*



PHOTOMICROGRAPH

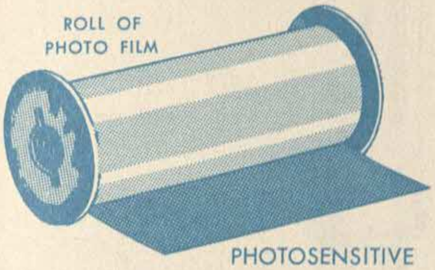
photon \'fō-ˌtän\ *n.*
PHYSICS. A unit of light energy equal to the quantum. It is considered to be a package, or bundle, of electromagnetic radiation that cannot be broken into smaller units and that travels at the speed of light; see *quantum* and *quantum theory of radiation.*

By absorbing a PHOTON, *an electron of an atom may gain enough energy to escape from the atom.*

photoperiodism \ˌfōt-ə-'pir-ē-ə-ˌdiz-əm\ *n.*
BIOLOGY. The reaction of plants and animals to the length of light each day. The amount of light regulates the time of flowering among certain plants and the time of molting among certain fur-bearing animals.

Nurserymen make use of the PHOTOPERIODISM *of chrysanthe-*

mums by controlling the length of light exposure to produce flowers for a longer season.

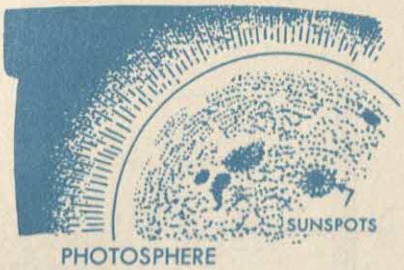


photosensitive \\,fōt-ə-'sen(t)-sət-iv\\ *adj.*
CHEMISTRY and PHYSICS. Referring to a substance that will undergo a chemical change, emit energy or produce some other effect as a direct result of absorbing radiant energy, especially light energy.

The emulsion on photographic film is PHOTOSENSITIVE.

photosphere \\'fōt-ə-,sfi(ə)r\\ *n.*
ASTRONOMY. The visible, gaseous layer that surrounds the sun or other stars. The photosphere of the sun has a thickness of a few hundred miles and a temperature of about 5,500° C.

Granules, sunspots and faculae all appear in the sun's PHOTOSPHERE.

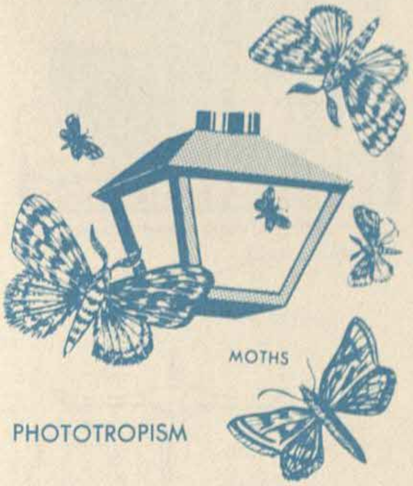


photosynthesis \\,fōt-ə-'sin(t)-thə-səs\\ *n.*
BOTANY and CHEMISTRY. The process by which sugar is manufactured in plant cells. It occurs through the combination of carbon dioxide and water in the presence of light and the catalyst chlorophyll, and is summarized by the equation $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$.

Through PHOTOSYNTHESIS, *plants manufacture their own food.*

phototransistor \\,fōt-ə-tranz-'is-tər\\ *n.*
ENGINEERING and PHYSICS. A semiconductor device that acts as a photoconductive cell.

The exposure meter used by photographers contains a PHOTOTRANSISTOR *that measures light intensity and activates a readable scale.*



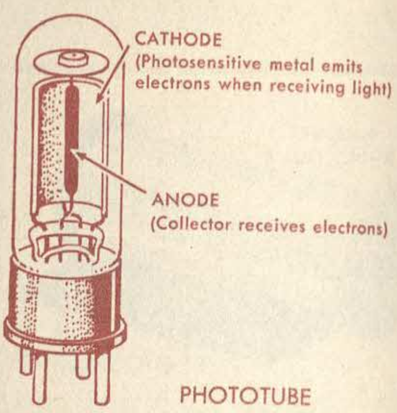
phototropism \\fō-'tä-trə-,piz-əm\\ *n.*
BIOLOGY. A movement reaction to light by plants and animals. The movement may be toward or away from light (positive or negative phototropism) and can be influenced by the wavelength of the light.

Moths that fly toward porch lights show positive PHOTOTROPISM, *while plant roots show negative phototropism.*

phototube \\'fōt-ə-,t(y)üb\\ *n.*
PHYSICS. A vacuum tube in which light strikes a photosensitive surface, causing free electrons to be given off. The electrons

move toward a positively-charged plate, forming an electric current. The number of electrons released depends on the intensity of the light. Such a tube is often used where light intensity must control the flow of electric current.

A PHOTOTUBE *is used in the device that reproduces sound recorded on a motion picture.*


CATHODE
(Photosensitive metal emits electrons when receiving light)
ANODE
(Collector receives electrons)
PHOTOTUBE

pH scale \pē-'āch 'skāl\

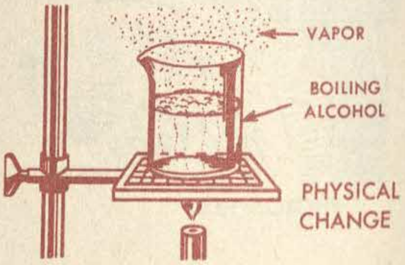
CHEMISTRY and PHYSICS. A numerical scale from 0 to 14, used to express the relative acidity or alkalinity of solutions. The actual value of a given solution is determined by the concentration of hydrogen (hydronium) ions in a solution in which water is the solvent. On the scale, 7 is neutral, values greater than 7 are alkaline and values less than 7 are acid.

Because the pH SCALE *is logarithmic, a solution with a* pH *value of 5 is ten times as acidic as a solution with a* pH *of 6.*

phylogeny \fī-'läj-ə-nē\ *n.*

BIOLOGY. The evolutionary history of a species or a race; see *ontogeny.*

The development, or ontogeny, of the human embryo appears to represent the PHYLOGENY *of man.*



phylum \'fī-ləm\ *n.*

BIOLOGY. A division of animal and plant classification that includes one or more classes and is itself included with other phyla in a kingdom.

Man belongs to the kingdom Animalia, the PHYLUM *Chordata and the class Mammalia.*

physical change \'fiz-i-kəl 'chānj\

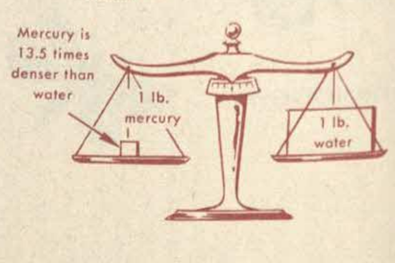
PHYSICS. A change in the physical state or properties of a substance. This change occurs through such processes as melting, evaporating and dissolving and does not result in a new substance with different chemical properties.

Alcohol undergoes a PHYSICAL CHANGE *from a liquid to a vapor when it boils.*

physical chemistry \'fiz-i-kəl 'kem-ə-strē\

CHEMISTRY. The branch of science that deals with physical changes that accompany or cause chemical reactions.

A large part of PHYSICAL CHEMISTRY *is concerned with properties of, and chemical changes in, solutions.*


ELECTRONS
ATOMS
−
+
Moving electrons constitute electric current
CONDUCTIVITY
PHYSICAL PROPERTY
DENSITY
Mercury is 13.5 times denser than water
1 lb. mercury
1 lb. water

physical property \'fiz-i-kəl 'präp-ərt-ē\

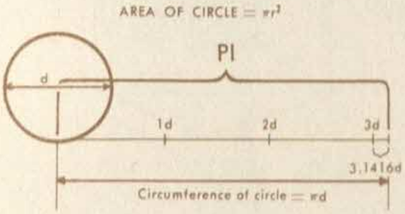
A quality or characteristic of a substance or body, such as density or electrical conductivity. The quality or characteristic does not involve a chemical change.

Electrical conductivity is a PHYSICAL PROPERTY *of silver.*

physicist \'fiz-(ə-)səst\ *n.*

PHYSICS. A person who is trained in, and who works in, the science of physics.

A PHYSICIST *may specialize in such areas as biophysics or astrophysics.*



physics \'fiz-iks\ *n.*

The branch of science dealing mainly with matter and energy and their interactions. It is subdivided into such areas as mechanics, optics, electricity, magnetism, acoustics and radiation.

Nuclear physics, one of the most recently-developed areas of PHYSICS, *includes the study of atomic fission and atomic fusion.*

physiologist \ˌfiz-ē-'äl-ə-jəst\ *n.*

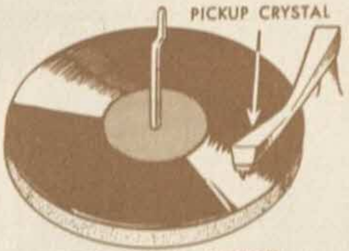
PHYSIOLOGY. One trained in the science of physiology.

A doctor is, to a large extent, a PHYSIOLOGIST.

physiology \ˌfiz-ē-'äl-ə-jē\ *n.*

The science that deals with the functions of cells, tissues, organs and systems in living organisms.

The study of photosynthesis is one phase of plant PHYSIOLOGY.



PIEZOELECTRIC EFFECT

pi \'pī\ *n.*

MATHEMATICS. The Greek letter π, a symbol for the ratio of the circumference of a circle to its diameter, having an approximate numerical value of 3.14159.

The area of any circle is found by multiplying the square of its radius by PI.

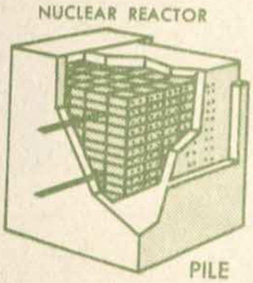
piezoelectric effect \pē-ˌā-(ˌ)zō-ə-'lek-trik i-'fekt\

PHYSICS. The phenomenon by which an electric voltage is produced between opposite ends of certain crystals when pressure is applied so that the crystal is shortened slightly; also, the reverse effect by which an applied voltage causes a crystal to expand or contract. Most practical applications involve vibrations rather than single movements, and alternating rather than direct current.

The PIEZOELECTRIC EFFECT *of a phonograph pickup crystal changes needle vibrations into electric pulses.*

pigment \'pig-mənt\ *n.*
1. CHEMISTRY. A finely-powdered, insoluble material used as a coloring agent in paints, cosmetics and ceramics. 2. BIOLOGY. A color-producing substance found in the tissues and cells of animals and plants.

Titanium dioxide is a white PIGMENT *used in many house paints.*

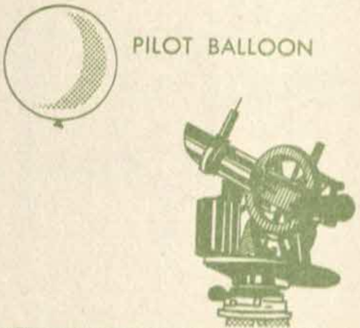


pile \pī(ə)l\ *n.*
1. PHYSICS. A nuclear reactor. 2. ENGINEERING. A concrete, wood or steel post driven into the ground to support a building, wharf or other structure.

PILE *was used to describe the first nuclear reactor, which was constructed by piling up blocks of graphite and chunks of uranium and uranium oxide.*

pillow lava \'pil-(,)ō 'läv-ə\
EARTH SCIENCE. Flows of lava that spread out into seas and lakes where they hardened into pillowlike masses.

PILLOW LAVA *may form when lava enters directly into the water from an underwater source.*



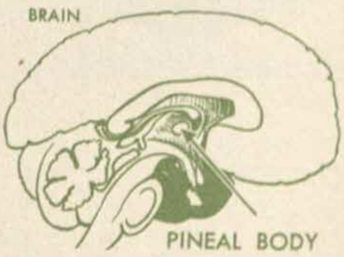
METEOROLOGIST USES THEODOLITE TO FOLLOW COURSE OF BALLOON

pilot balloon \pī-lət bə-'lün\
EARTH SCIENCE. A small balloon sent aloft by weather observers to determine the speed and direction of wind.

The PILOT BALLOON *is sometimes used in determining the height of a cloud ceiling.*

pinch effect \'pinch i-'fekt\
PHYSICS. The squeezing force on a conductor, resulting from electric current flow through the conductor. Electric currents flowing in the same direction through a conductor produce magnetic fields that attract each other, producing a squeezing force that can be large for currents of 100,000 amperes or more if the conductor is about one inch in diameter. The squeezing force is most noticeable if the conductor is a plasma, an ionized gas or a liquid.

The PINCH EFFECT *has been used in attempts to produce sustained nuclear fusion in a deuteron plasma.*



pineal body \'pin-ē-əl 'bäd-ē\
ANATOMY and ZOOLOGY. A cone-shaped gland located in the midbrain of man and present in all vertebrates. Thought to be a vestigial sense organ, it sometimes resembles an eye but has no known function.

The two main parts of a PINEAL BODY *are the pineal eye and the pineal organ.*

pinhole effect \'pin-,hōl i-'fekt\

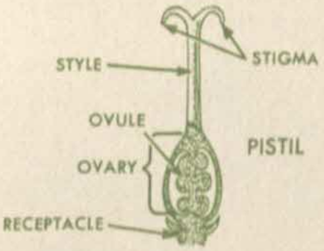
PHYSICS. The phenomenon by which an image of an object is formed on a screen by light passing through a very small opening in an opaque piece of cardboard or similar material.

A simple camera using the PINHOLE EFFECT *requires a much longer exposure time than a camera with a lens.*

pinnate \'pin-,āt\ *adj.*

BOTANY. Resembling, or referring to, the leaf pattern formed by leaflets that are opposite each other on the petiole or that alternate on the sides of a single midrib; also, referring to a pattern of side veins from a midrib on a leaf.

The leaflets of the locust tree are PINNATE.



pioneer biome \,pī-ə-'n(i)r 'bī-,ōm\

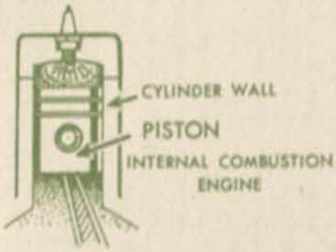
BIOLOGY and EARTH SCIENCE. One of the four major ecological divisions of the earth, the others being edaphic, climatic, and climax biomes.

In a PIONEER BIOME, *the influence of the physical environment is at a maximum, with the pioneer vegetation generally encountering extreme physical conditions.*

pistil \'pist-ᵊl\ *n.*

BOTANY. The female reproductive organs in a flower. The pistil is centrally located and usually includes the ovary, style and stigma.

Pollen adhering to the stigma of the PISTIL *may germinate and grow down through the style to the ovary.*



pistillate flower \'pis-tə-,lāt 'flau̇(-ə)r\

BOTANY. A flower that has pistils but no stamens, or no functional stamens.

A PISTILLATE FLOWER *is sometimes called an imperfect flower.*

piston \'pis-tən\ *n.*

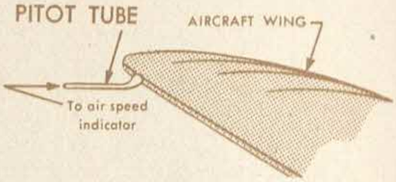
ENGINEERING. A close-fitting disk or solid cylinder that slides smoothly up and down in the barrel of a pump or in the hollow cylinder of an engine.

In a gasoline engine, a piston ring provides an airtight seal between the moving PISTON *and the cylinder wall.*

pitch \'pich\ *n.*

1. CHEMISTRY. A black, sticky substance obtained from the distillation of coal or petroleum; also, an amber, resinous substance obtained from certain pine trees. 2. PHYSICS. That property of

a tone determined by its frequency. 3. AERONAUTICS. The movement of an aircraft, rocket or other vehicle about a lateral axis; also, the angle at which a propeller blade or rotor blade meets the air. 4. ENGINEERING. The distance between two successive threads on a screw, or the distance a screw will advance when turned once.



PITCH is used for roofing, road building and calking.

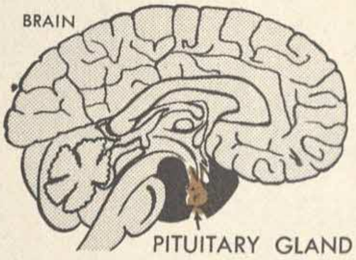
pitchblende \\'pich-ˌblend\\ *n.*

EARTH SCIENCE. The mineral uraninite, mostly UO_2, that is a black, lustrous, dense mineral ore containing uranium, radium, thorium and lead and is the chief ore of uranium.

The radium and lead found in PITCHBLENDE are radioactive decay products of uranium.

pith \\'pith\\ *n.*

1. BOTANY. Tissue, made up mostly of parenchyma cells, that forms the central core in dicotyledonous stems and roots and fills the spaces between vascular bundles in monocotyledonous stems and roots. 2. ZOOLOGY. The medulla; also, the soft tissue cells that form the core of a feather or a hair.



PITH is formed of thin-walled cells that eventually break down, leaving a partially-hollow root or stem.

Pitot tube \\ˌpē-'tō 't(y)üb\\

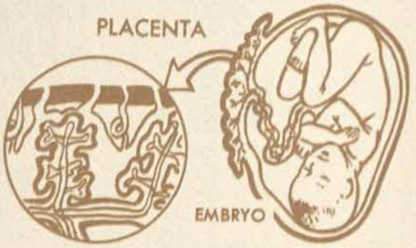
AERONAUTICS. An open-end tube used, along with a manometer, to measure the velocity of a gas or a liquid. The tube is placed in a moving fluid with the mouth pointed upstream.

A PITOT TUBE is used in most airplane air-speed indicators.

pituitary gland \\pə-'t(y)ü-ə-ˌter-ē 'gland\\

ANATOMY and ZOOLOGY. A ductless gland made up of two lobes and located at the base of the brain. The gland secretes a number of different hormones and is one of the most important glands of the body; also known as the pituitary body.

The PITUITARY GLAND secretes hormones that influence such glands as the adrenals and the thyroid.



placenta \\plə-'sent-ə\\ *n.*

1. ANATOMY and ZOOLOGY. A disk-shaped organ, rich in blood vessels and capillaries, that spreads over the inner surface of the uterus during the development of an embryo. It is found in most mammals. 2. BOTANY. A part of the ovary wall to which ovules are attached.

The PLACENTA and its attached umbilical cord carry nourish-

ment and oxygen from the mother to the embryo and waste products from the embryo to the mother's bloodstream.

placer deposit \'plas-ər di-'päz-ət\

EARTH SCIENCE. An accumulation of pebbles and sand, containing nuggets or flakes of gold, platinum, tin or other minerals. Such a deposit results from erosion of solid rocks.

Minerals are usually extracted from a PLACER DEPOSIT *by dredging, washing or other hydraulic methods.*

place value \'plās 'val-(,)yü\

MATHEMATICS. The value of a digit in a number as determined by its position relative to the units place.

In 25, 5 is in the units place and the PLACE VALUE *of 2 is 20 units.*

plain \'plān\ *n.*

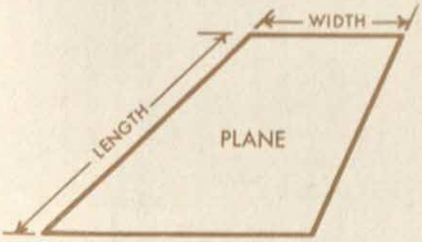
EARTH SCIENCE. A relatively-large, level surface of the earth; a surface with only small variations in elevation.

A PLAIN *may occur as an extensive valley floor, as a plateau or along a coast.*

Planck's law \'pläŋks 'lȯ\

PHYSICS. A theory stating that electromagnetic radiation interacts with matter as if the radiation were small bundles of energy (quanta). The amount of energy in a particular bundle (quantum) depends on the wavelength of the energy.

The mathematical expression for PLANCK'S LAW *is* $E = h\nu$, *in which E is energy in ergs,* ν *is frequency of radiation in cycles per second and h is a constant,* 6.624×10^{-27} *erg-seconds.*



plane \'plān\ *n.*

MATHEMATICS. A surface whose points are such that a straight line joining any two of them lies in the surface.

A PLANE *has length and width but no thickness.*

plane geometry \'plān jē-'äm-ə-trē\

MATHEMATICS. That part of geometry dealing with the logical treatment and study of the properties, characteristics and relationships of such plane figures as straight lines, angles, circles and polygons.

PLANE GEOMETRY *deals with two-dimensional figures, while solid geometry deals with three-dimensional figures.*

plane mirror \'plān 'mir-ər\

PHYSICS. A flat, smooth, highly-polished surface that reflects light and forms images. It may be made of metal or glass, backed with silver.

The image seems to be as far behind a PLANE MIRROR *as the object is in front of it.*

planet \'plan-ət\ *n.*

ASTRONOMY. Any one of the nine most prominent celestial bodies that revolve around the sun; also, a similar object that may revolve around another star; see table, page 618.

Pluto, the last PLANET *to be discovered, is about 40 times farther from the sun than is the earth.*

planetarium \ˌplan-ə-'ter-ē-əm\ *n.*

ASTRONOMY. A device that projects a reproduction of the heavens, at any given time and place, on the inside surface of a rounded dome and that duplicates the movements of the sun, moon, planets and other celestial bodies; also, the building or room having a dome and projector; also, a mechanical model of the solar system.

A PLANETARIUM *may be equipped to project the zodiac, ecliptic and solar circles and the Milky Way, as well as the stars, the planets and the moon.*

PLANETARIUM

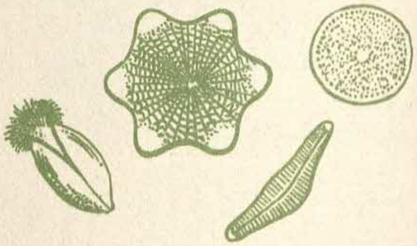
plankton \'plaŋ(k)-tən\ *n.*

BIOLOGY. Floating or weakly-swimming microscopic or near-microscopic plants and animals at the surface of a body of water.

The whalebone whale feeds exclusively on PLANKTON.

PLANKTON

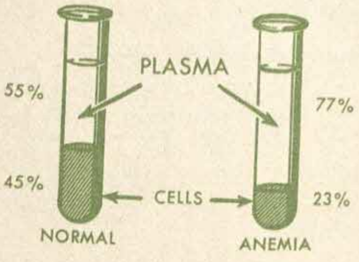
DIATOMS



plant \'plant\ *n.*

BOTANY. Any living organism not of the animal kingdom, including seed plants, ferns, mosses, algae, molds, lichens and bacteria. Plants are usually capable of food manufacture by photosynthesis and their cells are often surrounded by cellulose walls.

Even though a PLANT *may appear to be inactive and otherwise different from animals, it carries out the same life processes generally characteristic of an animal.*

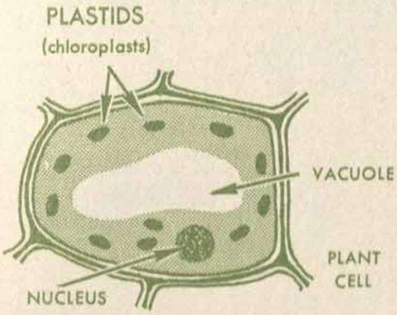


plasma \'plaz-mə\ *n.*

1. MEDICINE and PHYSIOLOGY. A straw-colored, sticky fluid, composing more than half of blood and containing proteins, inorganic materials, digested food and wastes. It is sometimes dried, stored and used for transfusions when whole blood is not available or suitable. 2. PHYSICS. A gas composed of electrically-charged particles with an equal, or nearly-equal, number of

free electrons and positive ions. It is formed only at temperatures higher than 50,000° C. and is believed to be the state of matter in stars.

In the process of obtaining blood serum for transfusions, the blood-clotting protein, fibrinogen, is removed from the PLASMA.



plasma physics \'plaz-mə 'fiz-iks\

PHYSICS. A branch of physics concerned with the electromagnetic control of plasma; see *plasma* (2).

One practical concern of scientists specializing in PLASMA PHYSICS *is the development of a rocket engine in which plasma is accelerated to extremely-high exhaust velocities.*

plasmolysis \plaz-'mäl-ə-səs\ *n.*

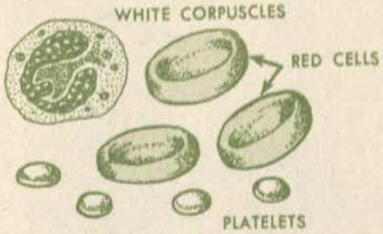
BIOLOGY. Shrinkage of cytoplasm within cells, caused by loss of water from the cells.

A plant wilts when there is a general PLASMOLYSIS *in the cells of the supporting tissues.*

plastic \'plas-tik\ *adj.*

1. PHYSICS. Capable of being shaped or molded by pressure. 2. CHEMISTRY. Referring to an object made from any one of a group of synthetic polymers or from mixtures of polymers with other substances.

Ordinary laboratory glass tubing is PLASTIC *at temperatures of 400° C. and higher.*



PLATELET

plastids \'plas-tədz\ *n.*

BIOLOGY. Bodies in the cytoplasm of most plants and one-celled organisms that are associated with the formation or storage, or both, of food. When pigmented, they are called chromoplasts.

Photosynthesis occurs in chlorophyll-containing PLASTIDS *called chloroplasts.*

plateau \pla-'tō\ *n.*

EARTH SCIENCE. An elevated plain; a plain considerably above sea level or above surrounding land areas. A plateau may be cut by canyons or valleys or interrupted by mountains.

A PLATEAU *usually has at least one side that is a steep slope to lower land.*

platelet \'plāt-lət\ *n.*

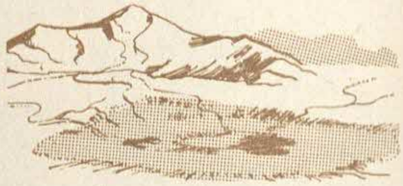
ANATOMY. An irregularly-shaped, colorless body that is the smallest of the solid particles in the blood. It plays an important role in blood clotting and is also called a thrombocyte.

A PLATELET *is about one-third to one-half the diameter of a red blood corpuscle.*

platinum \'plat-nəm\ *n.*

CHEMISTRY. A metallic element that is highly resistant to oxidation and corrosion by most chemicals. It is used for making jewelry, laboratory apparatus that must withstand high temperatures and chemical attack and as a catalyst for certain chemical reactions. Symbol, Pt; atomic number, 78; atomic weight, 195.09.

Since PLATINUM *expands and contracts with temperature changes at about the same rate as glass, it is frequently used when a wire must be sealed into a glass tube.*



PLAYA LAKE

playa lake \'plī-ə 'lāk\

EARTH SCIENCE. A temporary lake in an arid or semiarid region. It is formed in a flat basin or an undrained area by a heavy rain.

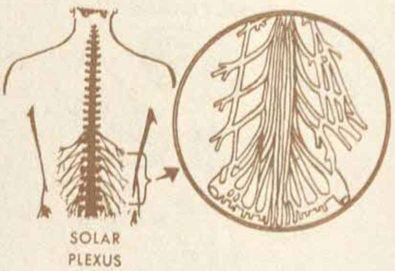
A PLAYA LAKE *evaporates quickly and leaves an alkaline mud flat, or playa.*

pleura \'plůr-ə\ *n.*

ANATOMY and ZOOLOGY. In man and other mammals, a thin membrane that covers each lung and folds back to form a lining for the inside of the thoracic cavity. The pleura secretes a mucus that permits free motion of the lungs in breathing; also, in arthropods, such as crayfish, shrimp or spiders, a heavy membrane that lines each side of a segment.

A pleural cavity is formed between the PLEURA *covering the lungs and that lining the chest.*

PLEXUS



plexus \'plek-səs\ *n.*

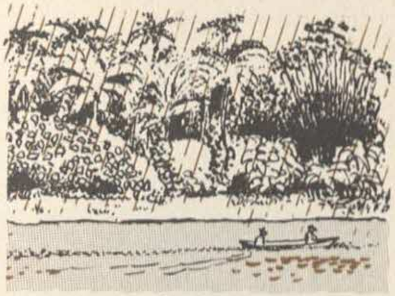
ANATOMY and ZOOLOGY. An interlacement, or network, of nerves, veins or lymphatic vessels.

The solar PLEXUS *located behind the stomach branches out to all of the organs within the abdominal cavity.*

plutonic \plü-'tän-ik\ *adj.*

EARTH SCIENCE. Referring to a rock body of igneous origin; formed from molten rock.

Granite is a PLUTONIC *rock that formed far below the earth's surface.*



PLUVIAL
(CLIMATE)

pluvial \'plü-vē-əl\ *adj.*

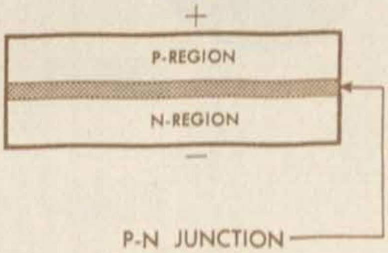
EARTH SCIENCE. Referring to rain, the action of rain or a period of abundant rain.

Tropical forests and jungles have a PLUVIAL *climate.*

pneumatics \n(y)ů-'mat-iks\ *n.*

PHYSICS. The branch of physics that deals with the mechanical properties of gases.

The air regulator in scuba (self-contained underwater breathing apparatus) equipment is an example of applied PNEUMATICS.



P-N JUNCTION
(IN SOLAR CELL)

p-n junction \'pē-,en 'jəŋ(k)-shən\

PHYSICS. The boundary between a p-region and an n-region in a transistor or other semiconductor. The p-region contains a trace of metallic impurity with a valence of +3, while the n-region contains a similar impurity with a valence of +5. When applied voltage forces electric current from the n-region to the p-region, the current meets very little resistance, but when voltage is applied in the opposite direction, the current meets great resistance and little, or no, current flows.

A crystal containing a P-N JUNCTION *can be used as a rectifier to change alternating current into pulsed direct current.*

point \'pȯint\ *n.*

MATHEMATICS. A geometric element that has position but no length, breadth, thickness or size.

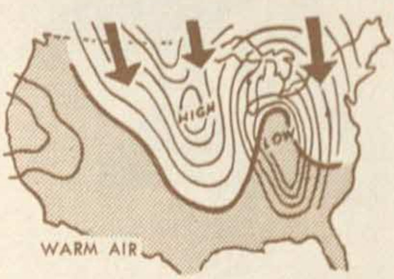
The place where two lines intersect is the POINT *at which they meet.*

poikilothermic \(,)pȯi-,kil-ə-'thər-mik\ *adj.*

ZOOLOGY. Referring to an animal that does not maintain a body temperature independent of environment; cold-blooded; see *homoiothermic.*

The body temperature of a POIKILOTHERMIC *organism such as a toad or a frog is usually only slightly higher than the temperature of the air or water around it.*

POLAR AIR MASS



polar air mass \'pō-lər 'a(ə)r 'mas\

EARTH SCIENCE. A body of air that originates or acquires its characteristics in polar regions and that moves toward lower latitudes.

A summer POLAR AIR MASS *usually brings fair weather to the central and eastern United States.*

polar body \ˈpō-lər ˈbäd-ē\

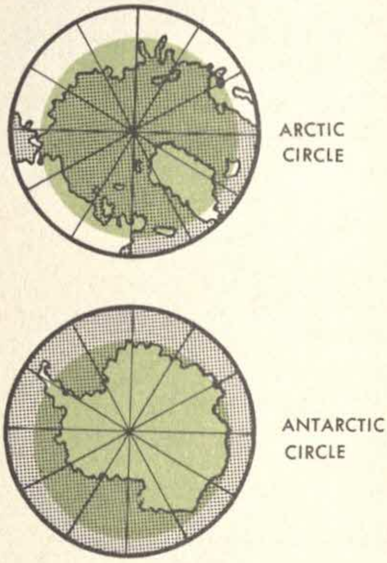
BIOLOGY. A small, nonfunctional cell produced during the meiotic divisions of egg production. It contains almost no cytoplasm and may divide again if formed during the first meiotic division.

A POLAR BODY *degenerates soon after formation.*

polar circle \ˈpō-lər ˈsər-kəl\

EARTH SCIENCE. Either the Arctic circle, 23½ degrees from the North Pole, or the Antarctic circle, 23½ degrees from the South Pole.

The part of the earth's surface within a POLAR CIRCLE *is classified as a frigid zone.*



POLAR CIRCLE

polar compound \ˈpō-lər ˈkäm-ˌpaůnd\

CHEMISTRY. A compound that will conduct electricity when melted or dissolved in water. It is usually a crystalline substance composed of two or more kinds of ions; an ionic compound.

Table salt is a POLAR COMPOUND, *but sugar, although crystalline, is not a polar compound.*

polar covalence \ˈpō-lər (ˈ)kō-ˈvā-lən(t)s\

CHEMISTRY. The sharing of a pair of electrons between two unlike atoms in which the pair of electrons is attracted more by one atom than by the other.

POLAR COVALENCE *applies to the bonding in a water molecule.*

polar front \ˈpō-lər ˈfrənt\

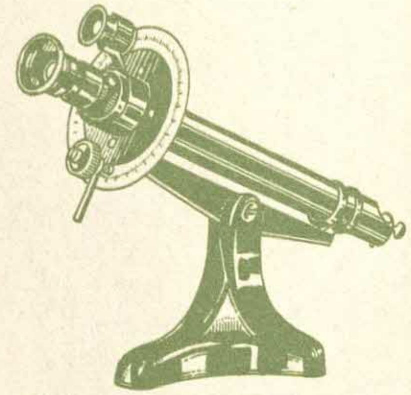
EARTH SCIENCE. A surface or boundary between a polar air mass and a tropical air mass.

In the Northern Hemisphere, a POLAR FRONT *moves farther south in winter than in summer.*

polarimeter \ˌpō-lə-ˈrim-ət-ər\ *n.*

CHEMISTRY and PHYSICS. An instrument that measures angular rotation of plane-polarized light passing through a liquid. The amount of angular rotation depends on the optical activity of the liquid.

A POLARIMETER *can be used to determine the concentration of certain sugar solutions.*



POLARIMETER

polarity \pō-'lar-ət-ē\ *n.*

PHYSICS. A condition in which two points of an object or system have different electrical, magnetic or other characteristics.

A coil of wire has magnetic POLARITY *only when a current of electricity flows through it.*

POLAR PROJECTION

polarization of light \ˌpō-lə-rə-'zā-shən əv 'līt\

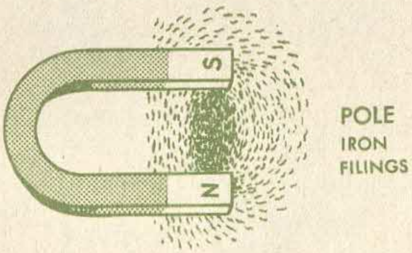
PHYSICS. The production of a beam of light in which all the electromagnetic waves vibrate in one plane. Light so produced is plane-polarized light.

POLARIZATION OF LIGHT *occurs when light passes through certain filters or is reflected at certain angles from a nonmetallic surface.*

polar molecule \'pō-lər 'mäl-i-ˌkyü(ə)l\

CHEMISTRY. A covalent molecule, with an unequal distribution of electric charges, that is positively charged at one end and negatively charged at the other end; a molecule in which the center of negative charge does not coincide with the center of positive charge.

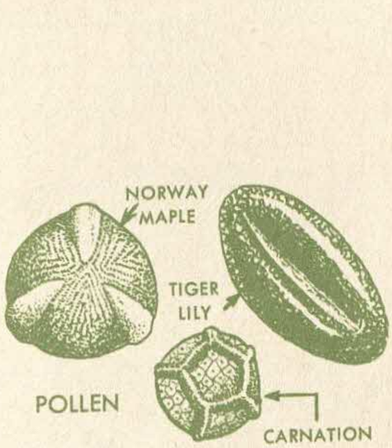
A water molecule is a POLAR MOLECULE *that underlies water's ability to dissolve such ionic substances as salt and copper sulfate.*



polar projection \'pō-lər prə-'jek-shən\

EARTH SCIENCE. A map of a polar region made by projecting the surface features onto a plane surface tangent to the earth at the geographical pole; a gnomonic projection of a polar region with the pole located at the center.

In a POLAR PROJECTION *the meridians appear as straight converging lines, and the parallels of latitude appear as concentric circles.*



pole \'pōl\ *n.*

1. PHYSICS. A point from which magnetic or electric fields appear to come; also, an electrical connection through which electricity will flow. 2. EARTH SCIENCE. A point on a sphere where its axis of rotation intersects the surface. 3. MATHEMATICS. Either of the two points at which a diameter perpendicular to a circle of a sphere intersects the sphere; the origin of the polar coordinate system.

The metal knob on the top of a flashlight cell is an electrically-positive POLE.

pollen \'päl-ən\ *n.*

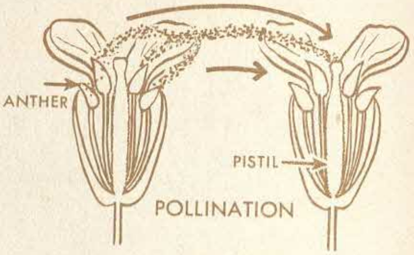
BOTANY. Grains producing male sex cells. Pollen is formed in the anthers of flowers or in the male cones of evergreens and often appears as a yellow, white or red dust; also called microspores.

POLLEN *made to germinate on microscope slides allows a detailed study of the male gametophyte.*

pollination \ˌpäl-ə-ˈnā-shən\ *n.*

BOTANY. A transfer of pollen from anther to pistil by wind, water, animals, gravity or, artificially, by plant breeders.

Fertilization of ova may follow POLLINATION.



POLLINATION

polychromatic light \ˌpäl-i-krō-ˈmat-ik ˈlīt\

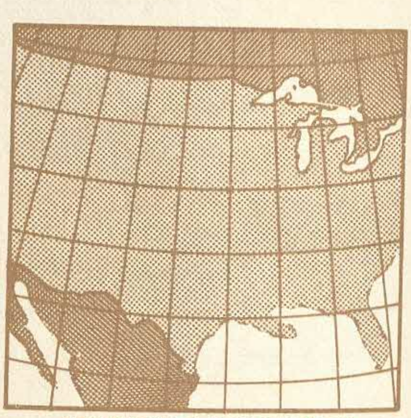
PHYSICS. Light made up of many colors, or wavelengths.

Sunlight is POLYCHROMATIC LIGHT.

polyconic projection \ˌpäl-i-ˈkän-ik prə-ˈjek-shən\

EARTH SCIENCE. A map of a part of the earth's surface. Lines on the map that represent parallels of latitude are spaced in proportion to their distance apart on a globe. Hence, each parallel is a curved line as would appear on a cone tangent to the earth at that parallel. The central meridian appears as a straight north-south line, while all other meridians are curved lines converging toward the central meridian.

A POLYCONIC PROJECTION *is normally used only for small areas because it distorts land areas as the distance from the central meridian increases.*



POLYCONIC PROJECTION

polyethylene \ˌpäl-ē-ˈeth-ə-ˌlēn\ *n.*

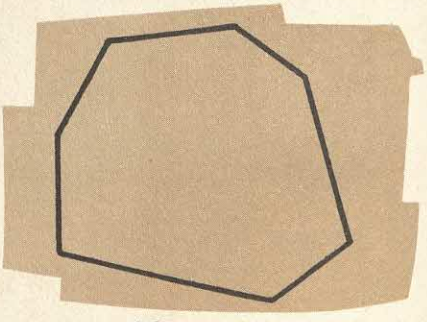
CHEMISTRY. One of a group of thermoplastics, usually manufactured as a thin sheet, that are used in food storage, garment protection and electrical insulation, and in a number of other areas where insulation or protection from moisture or chemicals is necessary.

Foods are often frozen in bags made of POLYETHYLENE.

polygon \ˈpäl-i-ˌgän\ *n.*

MATHEMATICS. A closed plane figure formed by straight line segments, or sides, so that no two consecutive segments lie in the same straight line or no three or more segments have a point in common.

A POLYGON *has as many interior angles as it has sides.*

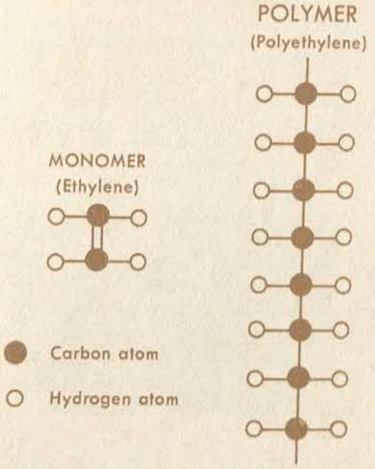


POLYGON

polygraph \ˈpäl-i-ˌgraf\ *n.*

MEDICINE and PHYSIOLOGY. An instrument used to record several different electrical or mechanical impulses simultaneously, such as pulse waves, blood pressure, respiratory movement and brain waves; popularly called a lie detector.

A POLYGRAPH *can be used to detect the physiological reactions that occur when a subject is not telling the truth.*



polyhedron \ˌpäl-i-ˈhē-drən\ *n.*
MATHEMATICS. A closed geometric solid formed by portions of plane surfaces called faces.

The faces of a POLYHEDRON *intersect in straight lines called the edges of the polyhedron.*

polymer \ˈpäl-ə-mər\ *n.*
CHEMISTRY. A compound of high molecular weight produced when small molecules link together to form larger molecules in a long chain.

Polyisoprene, which is similar in structure to natural rubber, is a POLYMER *of isoprene.*

polymerization \pə-ˌlim-ə-rə-ˈzā-shən\ *n.*
CHEMISTRY. A process by which two or more individual molecules (monomers) combine to form a large molecule (polymer). Usually, many small molecules join to form one very large molecule with a molecular weight of several thousand. It is used to produce such products as plastics and synthetic fibers.

When styrene molecules in liquid form undergo POLYMERIZATION, *they form polystyrene, a solid plastic often used to make cases for small radios.*

POLYMORPHISM

polymorphism \ˌpäl-i-ˈmȯr-ˌfiz-əm\ *n.*
BIOLOGY. The occurrence of different forms within one species, as the female worker and queen among social insects and the medusa and polyp among coelenterates.

The Portuguese man-of-war, made up of stinging, floating, feeding and reproductive individuals, exhibits complex POLYMORPHISM.

polynomial \ˌpäl-i-ˈnō-mē-əl\ *n.*
MATHEMATICS. An algebraic expression having one or more terms, but popularly considered to have two or more terms.

A POLYNOMIAL *having three terms is called a trinomial.*

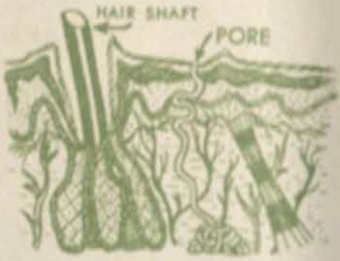
polysaccharide \ˌpäl-i-ˈsak-ə-ˌrīd\ *n.*
CHEMISTRY. Any one of several carbohydrate compounds that

will react with, or decompose in, water to form two or more simple sugars (monosaccharides).

Ordinary cornstarch is a POLYSACCHARIDE.

population \ˌpäp-yə-ˈlā-shən\ *n.*
1. BIOLOGY. The living organisms that inhabit a given area or region. 2. MATHEMATICS. A given group of objects, people or things from which statistical observations or samples are drawn.

The elm tree POPULATION *of the United States has been seriously depleted by blight.*



pore \ˈpō(ə)r\ *n.*
ANATOMY and BIOLOGY. A small opening in skin or in membranes, that may function in secretion, excretion, transpiration or absorption processes.

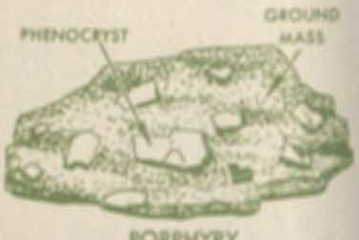
Infection may enlarge a sweat gland PORE.

porosity \pə-ˈräs-ət-ē\ *n.*
The quality of being able to absorb, or being permeable to, liquids and gases.

The POROSITY *of a sponge is such that it can absorb several times its own weight of water.*

porphyry \ˈpȯr-f(ə-)rē\ *n.*
EARTH SCIENCE. An igneous rock composed of large crystals, called phenocrysts, in a groundmass or matrix of fine mineral grains. Each deposit is named after the predominant rock material in it, such as granite porphyry or basalt porphyry.

To be classified as a PORPHYRY, *a rock must contain 25 percent or more phenocrysts.*



PORPHYRY

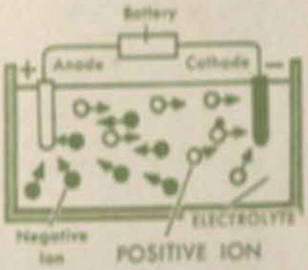
positive \ˈpäz-ət-iv\
1. MATHEMATICS (Adj.). Referring to any real number, any integer or any quantity greater than zero. 2. PHYSICS (N.). A photographic print on paper or transparent film.

A POSITIVE *number is sometimes indicated by a plus (+) sign, as +3.*

positive charge \ˈpäz-ət-iv ˈchärj\
PHYSICS. The fundamental unit of electricity carried by a proton; also, the kind and amount of electric charge remaining when a hydrogen atom loses one electron; also, the electrical

condition produced on an electrically-neutral object when the object loses electrons.

A POSITIVE CHARGE *produced on a glass rod by rubbing it with a silk cloth produces an equal negative charge on the silk cloth.*



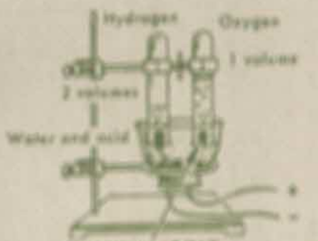
POSITIVE ION

positive ion \'päz-ət-iv 'ī-ən\
CHEMISTRY and PHYSICS. An atom or a group of atoms that has lost one or more electrons and has a positive electric charge as a result.

In the electrolysis of hydrochloric acid, each POSITIVE ION *is attracted to the negative electrode.*

positive pole \'päz-ət-iv 'pōl\
PHYSICS. One of the two terminal points (positive and negative) in an electric circuit. It attracts electrons or other negatively-charged objects by its positive charge.

When water is decomposed by electricity, oxygen is released at the POSITIVE POLE *and hydrogen at the negative pole.*



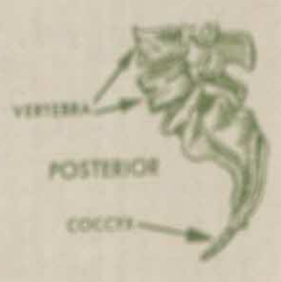
POSITIVE POLE

positron \'päz-ə-,trän\ *n.*
CHEMISTRY and PHYSICS. A subatomic particle having the same mass as an electron but carrying a single positive electric charge, whereas an electron carries a single negative electric charge.

When a POSITRON *interacts with an electron, they both disappear, forming gamma radiation in their place.*

posterior \pä-'stir-ē-ər\ *adj.*
ANATOMY and ZOOLOGY. Referring to a part that is situated behind another part or toward the rear; also, toward the back, or dorsal surface; also, in a direction away from the head end of an animal that is bilaterally symmetrical.

The coccyx, or tailbone, is at the POSTERIOR *end of the vertebral column.*



POSTERIOR

postulate \'päs-chə-lət\ *n.*
MATHEMATICS. A proposition or statement of a deductive system, such as geometry, that is accepted without proof and from which other statements may be deduced.

The word POSTULATE *usually has the same meaning as the word axiom.*

potable water \'pōt-ə-bəl 'wȯt-ər\
CHEMISTRY. Water safe for drinking, or made suitable for drinking.

POTABLE WATER *can be made from sea water through the process of desalinization.*

ABBREVIATIONS

A	ampere
Å	Ångstrom unit
abs	absolute
a-c	alternating current (as an adjective)
amu	atomic mass unit
atm	atmosphere
at. wt	atomic weight
AU	astronomical unit
avdp	avoirdupois
Bev	one billion electron volts
bhp	brake horsepower
bhp-hr	brake horsepower-hour
bp	boiling point
Btu	British thermal unit
C	temperature Celsius; temperature Centigrade
c	candle
cal	calorie
cfm	cubic feet per minute
cfs	cubic feet per second
cgs	centimeter-gram-second (system)
cl	centiliter
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
coef	coefficient
colog	cologarithm
cos	cosine
cot	cotangent
cp	candlepower
csc	cosecant
cu	cubic
cu ft	cubic foot
db	decibel
d-c	direct current (as an adjective)
doz	dozen
E	electromotive force
e	the base of the system of natural logarithms
ev	electron volt
F	temperature Fahrenheit
fp	freezing point
fpm	feet per minute
fps	feet per second
ft	foot; feet
ft^2	square foot
ft^3	cubic foot

ft-c	footcandle
ft-lb	foot-pound
G	universal gravitational constant
g	gram
gal	gallon
g-cal	gram-calorie
gpm	gallons per minute
gps	gallons per second
hr	hour
hν	photon energy
hp	horsepower
Hz	hertz (cycles per second)
I	electric current
ID	inside diameter
in.	inch
in.^{2}	square inch
in.^{3}	cubic inch
in.-lb	inch-pound
ips	inches per second
j	joule
K	temperature Kelvin (absolute)
kcal	kilocalorie
kg	kilogram
kg-cal	kilogram-calorie
kg-m	kilogram-meter
kg/m^3	kilograms per cubic meter
kgps	kilograms per second
km	kilometer
kv	kilovolt
kw	kilowatt
kwhr	kilowatt-hour
l	liter; lumen
lat	latitude
lb	pound
lb-ft	pound-foot
lb/ft^2	pounds per square foot
lb/ft^3	pounds per cubic foot
lb-in.	pound-inch
l-hr	lumen-hour
lin ft	linear foot
log	logarithm (common)
log$_e$	logarithm (natural)
long.	longitude
m	meter; minute (time, in astronomical circles)

m^2	square meter
m^3	cubic meter
ma	milliampere
Mev	one million electron volts
mg	milligram
mh	millihenry
mi	mile
mi^2	square mile
min	minute
m-kg	meter-kilogram
ml	milliliter
mm	millimeter
mm^2	square millimeter
mm^3	cubic millimeter
mμ	millimicron
mph	miles per hour
mphps	miles per hour per second
mv	millivolt
N	Avogadro's constant
n!	factorial *n*
OD	outside diameter
oz	ounce
pH	rating on acid-alkaline scale
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
R	temperature Reaumur; resistance
RA	right ascension
rpm	revolutions per minute
rps	revolutions per second
sec	secant; second
sin	sine
sp gr	specific gravity
sq	square
tan	tangent
V	volt
VA	volt-ampere
W	watt; work
yd	yard
yd^2	square yard
yd^3	cubic yard

SCIENTIFIC SYMBOLS AND ABBREVIATIONS

α	alpha particle
β; β^-	beta particle
β^+	positron
γ	gamma radiation
Δ	a small change; heat
λ	wavelength; radioactive-decay constant
ma	milliampere
μc	microcurie
μf	microfarad
μin.	microinch
μm	micron
$\mu\mu$	micromicron
$\mu\mu$f	micromicrofarad
ν	frequency; neutrino
π	3.14159; osmotic pressure

Σ	the sum of
σ	nuclear cross section (barns); area
Ω	electrical resistance (ohms)
ω	angular speed; angular velocity
$'$	minute (angular measure)
$''$	second (angular measure)
♂	male
♀	female
$>$	is greater than
$<$	is less than
$\propto$	is proportional to
∞	infinity
$\sqrt{}$	square root of
$^\circ$	degrees; temperature; angle measurement (example, 30°)

[ ]	molar concentration
$+$	positive electric charge; mixed with; plus
$-$	negative electric charge; single covalent bond; minus
$=$	equals; double covalent bond; produces
$\neq$	does not equal
$\equiv$	triple covalent bond
$\rightarrow$	produces; forms; chemical reaction
$\rightleftarrows$	reversible chemical reaction
$\uparrow$	gas produced by a chemical reaction
$\downarrow$	precipitate produced by a chemical reaction
$\bullet$	radioactive substance (follows symbol of element; example, Cl$^\bullet$)